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Measurement of capillary rise under field conditions and related soil properties

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Measurement of capillary rise under field conditions and related soil properties

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SUMMARY

Capillary rise, measured at two sites in one orchard over three experimental periods supplied from 45 to 79% of the water used by herbaceous cultures during these periods. The water table was unusually deep in 1978 and, because of the consequent low rates of rise, no measurement of capillary rise was possible in 1978; a reminder that capillary rise is a reliable source of water for plant growth only if water table depth is relatively stable. Hydraulic properties of core samples from the capillary rise sites fell well within the range of samples from eight other sites that represented the range of texture of orchard soils in the region (sand, loamy sand, sandy loam and loam). Thus, given similar water table depths, rise in many soils of the region, would probably equal or exceed the rise that was observed in the experimental orchard. Observed rise agreed closely (within a factor of 2) with rise calculated from core properties, water table depth and soil moisture tension on one site but cores from the second site were more variable and agreement was less good. Correlations between hydraulic properties and other soil properties suggest that capillary rise parameters were adversely affected by the high bulk density of these subsoils. Increase in bulk density was associated with a need for shallower water table (for a given flux) and a greater sensitivity of flux to change in water table depth. Percent sand and fineness of sand were the dominant textural controls of rise parameters. Capillary rise from water tables within subsoils of unusually high bulk density (approaching 2 g/cm^3) is not likely to supply appreciable water for plant growth under field conditions.

RÉSUMÉ

L'ascension capillaire, mesurée en deux endroits dans un verge au cours de trois périodes expérimentales, fournissait de 45 à 79% de l'eau utilisée par les cultures herbacées durant ce temps. En 1978, le niveau phréatique étant inhabituellement bas, la vitesse d'ascension a été faible de sorte qu'il a été impossible d'en faire la mesure cette année-là - ce qui rappelle que l'ascension capillaire n'est une source d'eau sûre pour les plantes en croissance que si la profondeur de la nappe phréatique est relativement stable. Les propriétés hydrauliques des carottes de sol prélevées des sites d'ascension capillaire se comparaient bien à celles de l'éventail d'échantillons carottés en huit autres endroits, échantillons qui représentaient la gamme de textures des sols des vergers de la région (sable, sable loameux, loam sableux et loam). Par conséquent, pour des niveaux phréatiques de profondeur semblable, l'ascension capillaire dans de nombreux sols de la région serait probablement égale ou supérieure à celle qui a été observée dans le verger expérimental. En un endroit, l'ascension observée correspondait étroitement (à un facteur de 2) à celle calculée d'après les propriétés de la carotte, la profondeur de la nappe phréatique et la tension de l'eau du sol, mais au deuxième endroit la valeur observées était plus variable et la correspondance moins bonne. Si l'on en juge d'après les corrélations entre les propriétés hydrauliques et d'autres propriétés du sol, les paramètres de l'ascension capillaire furent perturbés par la densité apparente de ces sous-sols. L'augméntation de la densité apparente a été associée au besoin d'une nappe phréatique moins profonde (pour un flux donné) et à une plus grande sensibilité du flux aux changements de profondeur de la nappe phréatique. Le pourcentage et la finesse du sable étaient les principaux contrôles texturaux des paramètres de l'ascension capillaire. L'eau montant par capillarité des nappes phréatiques qui se trouvent dans les sous-sols à forte densité apparente (approchant 2 g/cm^3) ne devrait pas suffire à en fournir une quantité appréciable pour assurer la croissance des plantes dans les conditions du terrain.

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INTRODUCTION

In a recent study of factors affecting rooting depth of apple trees (Webster 1978), one orchard (D) was unusual in several respects. Although rooting was shallow there was no apparent barrier to deep rooting; tree performance was better than is associated with shallow rooting and, within the zone of root development, roots were exceptionally abundant. These features led to the speculation that capillary rise from a water table contributed significantly to available water in this orchard and to the more general speculation that the contribution of capillary rise to available water may be appreciable in some, years on similar sites in this region.

Capillary rise is a dependable source of water for plant growth only under exceptional circumstances where natural or man-made features enable relatively stable water table depth regardless of weather conditions. In the more usual circumstances, where water table depth fluctuates widely depending upon weather conditions, capillary rise is of no practical interest. However, in the investigation of relationships between soil properties and crop performance, rise is of interest for research purposes if it can contribute to the water supply on some sites in some years because, if this contribution can not be estimated and segregated, it will be a source of experimental error.

This study was undertaken (1) to examine the magnitude of capillary rise in this orchard (orchard D), (2) to characterize, to a limited extent, the hydraulic properties of the subsoil under this orchard and (3) to compare the hydraulic properties of samples from Orchard D with hydraulic properties of samples representing the range of soil texture commonly used for apple orchards in this region.

MATERIALS AND METHODS

The experimental field (Sheffield Farm, Kentville Research Station field B2; orchard block 23) was mapped as Somerset in the most recent soil survey (Cann *et al.* 1965), slopes northward with a gradient of approximately 1:50 and was planted to orchard in 1962 at a spacing of 4.6 x 7.9 m. Capillary rise was measured at two vacant tree sites, row 2 tree 28 and row 2 tree 42.

Field measurement of capillary rise

GENERAL APPROACH. At each of these two sites, two iron cylinders were installed, filled 5 cm above ground level with disturbed soil (to allow for settling), and covered with raised translucent rain shelters. Early in each subsequent growing season soil was removed from all cylinders (topsoil segregated) and replaced, fertilizer being mixed in the top 20 cm. The soil in one cylinder (open) rested directly on the undisturbed subsoil. The soil in the second cylinder (closed) was isolated from the subsoil by means of a shallow iron tray with provision for sub-irrigation. After a cover of plant growth was established in th cylinders, volumetric soil moisture was measured (start to run; Table 1) and measured again after a period of 20 to 39 days (end of run; Table 1). During the course of a run soil moisture tension (gauge) was monitored at a depth of 40 cm in both cylinders and the closed cylinder was sub-irrigated as necessary to keep soil moisture tension in the closed and open cylinders approximately equal.

Evapotranspiration from the closed cylinder was considered to be,

$$EV_c = W_{cs} - W_{ce} + I \qquad (1)$$

and from the open cylinder

$$EV_o = W_{os} - W_{oe} + R \qquad (2)$$

where EV is evapotranspiration, the letters c, o, s and e refer to closed cylinder, open cylinder, start of run and end of run respectively, W is the soil moisture content (cm) within the cylinder, I is sub-irrigation and R is capillary rise. Assuming that $EV_c = EV_0$,

$$R = W_{cs} - W_{ce} + I - (W_{os} - W_{oe}) \qquad (3).$$

Class A pan evaporation records, for comparison with EV_c, were from the Kentville weather station located about 7 km from the capillary rise sites.

It was not practical to generate soil moisture tension in the cylinders with apple trees and a low-growing stand of closely spaced plants was therefore used for this purpose. For example, moisture extraction by a tree advances outward and downward from the trunk in a somewhat irregular way depending upon root location as opposed to the more uniform moisture extraction by a stand of closely spaced plants. Uniform extraction was needed in order to monitor moisture tension and maintain equal availability of water in the closed and open cylinders.

Further, the assumption of equal water usage from the closed and open cylinders is more likely to be approximated by a closely spaced stand of many plants than by one tree or several trees per cylinder. However, the results obtained by using a ground cover should apply equally to trees in the sense that flow, induced by a given moisture tension gradient, will be indifferent to the cause of the gradient.

CYLINDER DESIGN. Cylinders were 55 cm long, 107 cm in diameter, coated with asphalt emulsion paint and installed June 1977, 30 cm apart in the tree row to a depth of 50 cm by digging a hole, setting the cylinders in place and refilling. The tray for the closed cylinder, also asphalt coated, was 114 cm in diameter with a 10-cm high rim and a central drain connected by pipe to a shutoff, gravel-filled 30 L drain pit and a drain observation port (Fig. 1). The shut-off was closed during a run and left open over the dormant season so that free water, following periods of high water table, could drain from the tray.

The bottom of the tray was covered with 3 cm of medium sand and the cylinder rested on blocks 3 cm above the tray. The space between the cylinder wall and the tray rim was filled with pea gravel and the rim to cylinder gap was sheathed with a strip of 0.7 mm saran screen. A vertical 3.8 cm (ID) iron pipe, secured to the cylinder wall and leading to the bottom of the tray, was used for addition of sub-irrigation water, usually in amounts of 2 or 4 L. Water was added rapidly so as to get maximum flow around the rim and across the tray bottom. A second vertical pipe of 1.3 cm diameter copper was used with a bubbler tube to monitor free water height near the tray rim during addition of sub-irrigation water to insure that water did not overflow the tray rim.

This method of sub-irrigation that was used in 1977 (gravel in rim plus sand at bottom) led to unequal water distribution; soil nearest the sub-irrigation down pipe being more moist than soil on the opposite side of the cylinder. To provide uniform water distribution the bottom end of the sub-irrigation down pipe was capped and two concentric soft copper tubes (1.3 cm diameter tube in rings of 45 and 85 cm diameter) were attached to the down pipe. These rings were supported level, with the lower side 2 cm above the tray bottom, perforated on the lower side (1.6 mm diameter) and furnished with upright and loosely capped air vents on the side distal to the down pipe (Fig. 2). Perforations were spaced 4 cm apart on the inner ring and the proximal $^{1}/_{3}$ portion of the outer ring and 2 cm apart on the distal $^{2}/_{3}$ portion of the outer ring.

RAIN SHELTERS. Rain shelters were constructed from two panels (133 x 366 cm) of translucent corrugated fiberglass greenhouse covering secured to a light wooden frame to form a pitched shelter 368 cm long, 256 cm wide and with a pitch of 15 cm from each side to the center ridge and mounted with the ridge 90 and 75 cm above ground level on the up and down slope ends, respectively. Rain, collected from gutters on the down slope end, was conveyed by pipe a further 3 m down slope.

SOIL MOISTURE SAMPLES. A series of gouge shaped sampling augers (Eijkelkamp B.V.) 40, 35, 30, 25 and 20 mm diameter were used to take four soil samples, in relatively undisturbed condition, fro depths of 0-10, 10-20, 20-30, 30-40, and 40-50 cm respectively,

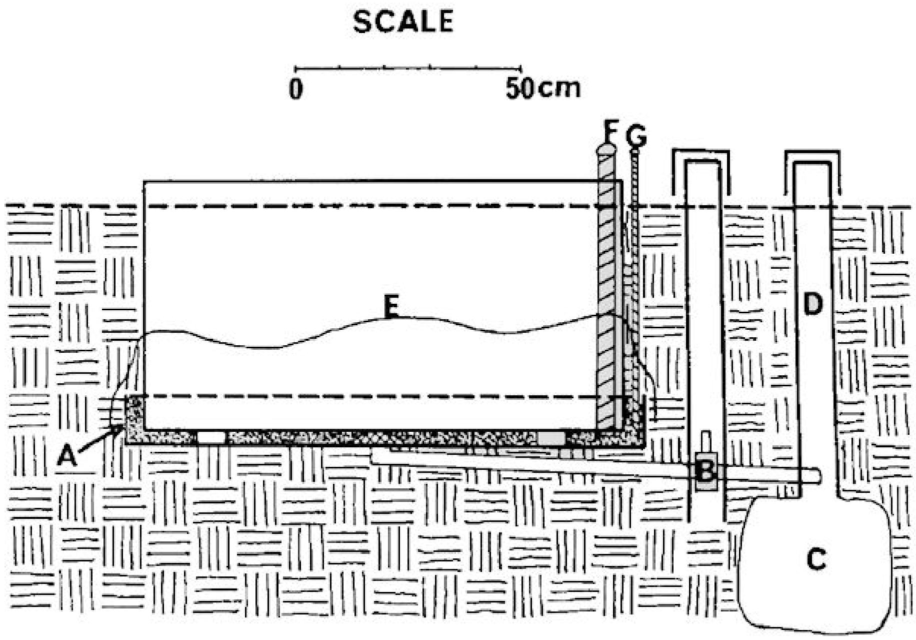

Fig. 1. Design of closed cylinder. Tray (A) with gravel-filled rim, and 3 cm of medium sand provided with central drain, shutoff (B), gravel-filled drain pit (C) and drain observations port (D) and sheathed with a strip of 0.7 mm saran screen (E).Pipes F and G were for addition of sub-irrigation water and measurement of water height near the tray rim during addition respectively.

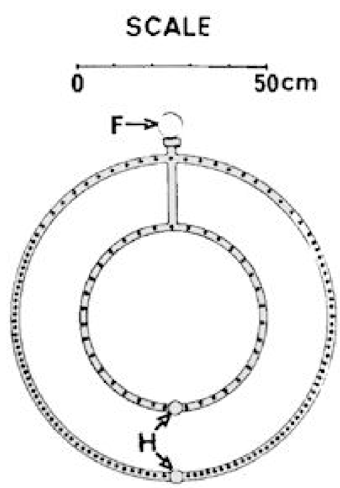

Fig. 2. Top view of perforated concentric copper water distribution tubes showing vertical iron down pipe (F) and loosely capped air vents (H).

Table 1. Schedule and particulars of capillary rise determinations at two sites.

Site, year	#1, 1977	#2, 1977	#1, 1979	#1, 1979	#2, 1979	#2, 1979
Rain shelters installed	25 July	26 July	25 May	25 May	25 May	25 May
Start of run	4 Aug	9 Aug	4 July	27 July	20 July	21 Aug
End of run	2 Sept	2 Sept	27 July	4 Sept	21 Aug	10 Sept
No of days	29	24	23	39	32	20
Closed cylinder						
Water at start (cm)	11.13	11.07	11.70	9.88	11.97	8.28
Water added (cm)	4.70	4.59	5.55	5.33	4.66	2.44
Water at end (cm)	8.89	10.03	9.88	7.27	8.28	7.19
Water use (cm)	6.94	5.63	7.37	7.94	8.35	3.53
(cm/day)	0.24	0.23	0.32	0.20	0.26	0.18
Class A pan evaporation (cm)	12.24	9.98	11.33	13.63	12.58	6.69
Use/class A pan	0.57	0.56	0.65	0.58	0.66	0.53
Open cylinder						
Water at start (cm)	10.42	11.38	12.60	8.58	11.80	8.12
Water at end (cm)	7.77	10.17	8.58	5.60	8.12	7.26
Capillary rise (cm)	4.3±1.7 †	4.4±1.6	3.3±1.6	5.0±1.5	4.7±1.0	2.7±1.0
(cm/day)	0.15	0.18	0.15	0.13	0.15	0.13
(% of water use)	62	79	45	62	56	76
Groundcover	sod ‡ transplanted 16 June 1977		Broccoli seedlings planted 45/cylinder 11 June, thinned to 25 plants.			

† Rise 95% confidence limits.

‡ Chiefly *Poa pratensis* L.

samples from opposite quarter positions being pooled. After1 trimming to know volume the samples were oven dried at 105°C for calculation of volumetric soil moisture and cm water over the 50 cm profile.

The 95% confidence limits for capillary rise were calculate as:

$$95\% \text{ limits} = 2.776 \ [\Sigma(\text{rep } 1- \text{ rep } 2)^2 /4]^{0.5}$$

with the duplicate determinations (rep 1 and rep 2) of W_{cs}, W_{ce}, W_{os} and W_{oe} entered into the summation.

SOIL MOISTURE TENSION. Tensiometer gauges were calibrated at four points (10, 20, 40 and 60 centibars) and two tensiometers were installed in each cylinder at a depth of 40 cm. Tensiometer readings, taken three to six times per week depending upon anticipated rate of change or need for irrigation were corrected for gauge bias and height from gauge to ceramic element.

WATER TABLE DEPTH. Five observation wells were installed July, 1977 along a line tangential to and about 1 m from each open cylinder by drilling holes 4.7 cm in diameter and about 0.5 m apart to depths of 60, 100, 170, 200 and 250 cm. These wells were cased with ABS pipe (3.8 cm ID, 4.76 cm OD) that had been slotted over depths of 30-54, 70-94, 100-164, 170-194 and 150-244 cm respectively with staggered 3-mm wide saw cuts at quarter positions. Wells were covered with a loose fitting cap.

Depth readings were taken with a bubbler rod three to six times per week, corrected with reference to the average soil surface elevation of the five wells at each site and averaged for a given day after editing out readings indicative of sluggish response (the bottoms of some wells became impermeable and outflow from these wells was very slow after the water table had dropped below the slotted section).

Laboratory measurements

SOIL SAMPLES. Cores of relatively undisturbed soil, 7.6 cm in diameter and 3 cm long, were taken within 1 m of the open cylinder at the two capillary rise sites and at eight other locations (Table 2), using a sampler similar to the one described by Swanson (1950). These eight locations were selected so that the range of soil texture common in apple orchard soils of the region would be represented. Both ends of the core samples were trimmed flush with the lucite retaining cylinders and the lower end was covered with 53 um nylon mesh (B. and S. H. Thompson and Co. Ltd., 235 Montpellier Blvd., Montreal) held in place with an

Table 2. Source of core samples.

Sample no.	Depth (cm top of core)	No. of cores	Soil type †	Texture of sample
9	45	1	Nictaux	sand
11	65	1	Berwick	sand
8	65	2	Somerset	sand
7	85	2	Debert	loamy sand
55 (Site#1)‡	70, 80	4	Somerset	sandy loam
99	85	2	Berwick	sandy loam
5 (Site#2) ‡	65, 80	4	Somerset	sandy loam
10	85	2	Berwick	sandy loam
13	85	2	Kentville	sandy loam
12	45	2	Middleton	loam-clay loam

† Soil series as described in Cann et al. (1965).

‡ Sites at which capillary rise was measured in field.

elastic band. This nylon mesh was not removed until conductivity and moisture retention determinations were completed. Additional soil was collected at the same time for determination of moisture retention at 15 bar, particle density (pycnometer, method 2.25 in McKeague ed. 1978), percent carbon (modified Walkley-Black, method 3.613 in McKeague ed. 1978) and particle size distribution (pipet method, method 2.111 in McKeague ed. 1978).

SATURATED HYDRAULIC CONDUCTIVITY. An empty core retaining cylinder 7.6 cm long and resting on a 1-mm wire screen disc (8.2 cm diam.) was fastened to the upper end of the core sample with a wide elastic band. Soil cores were then placed on a rigid support consisting of a disc of 0.5-mm nylon mesh overlying a perforated lucite disc provided with wire handles so that the entire assembly could be moved without disturbing the samples. Samples were moistened from below with de-aerated 0.01 N $CaSO_4$ containing 1 mL of 40% formaldehyde per litre and soaked in this solution a further 24 hours. After transfer of the core assembly to a funnel, hydraulic conductivity was determined at constant head as described by Klute (1965; pp 214-215) using a Mariotte bottle for head control. Average hydraulic conductivity was calculated as a geometric mean and the associated standard deviation accordingly implies multiplication and division not addition and subtraction.

MOISTURE RETENTION CURVE. Samples were weighed immediately after determination of saturated hydraulic conductivity, for calculation of moisture retention at zero tension, and moved to a tension table (along with concurrently soaked blank cores) for determination of moisture retention over the range of 5-500 cm water as described in Canadian Soc. Soil Sci. Methods Manual (McKeague ed. 1978; pp 43-44) but with minimum equilibration times approximately $^1/_6$ as long as those recommended for cores 7.6 cm long; the rationale being that time to reach equilibrium will vary approximately with the square of sample heights (Richards 1965; p 136).Tensions in cm water followed by bracketed minimum equilibration times in hours were as follows [3], 10 [4], 20 [4], 40 [10], 60 [10], 80 [15], 100 [24], 150 [30], 225 [38], 300 [45] and 500 [52]. The tension table design followed Topp and Zebchuk (1979) except that the tension medium was a 2-cm layer of 9.5 pm aluminum oxide powder for all tension and was covered with 53 pm nylon mesh. Mean moisture retention curves over two or more cores were calculated as the arithmetic mean at each tension point.

Retention at 1 bar (14.5 psi) was measured using a ceramic pressure plate with a thin layer of 9.5 pm aluminum oxide powder between the core sample and the ceramic surface. Retention at 15 bar was determined with the fine fraction (< 2-mm) of an air dried sub-sample using a ceramic pressure plate and expressed on a fractional volume basis after adjustment for coarse fraction (> 2-mm) content and core bulk density, i.e.

$$\theta_{15\ bar} = W_{15\ bar} \times f \times D_b$$

where $\theta_{15\ bar}$ is adjusted water content (cm^3/cm^3) at 15 bar, $W_{15\ bar}$ is g water retained at 15 bar per g fine soil, f is g fine soil per g unsieved soil, D_b is core bulk density (g/cm^3), fine soil refers to the fraction passing a 2-mm sieve and all soil weights are on an oven-dry (105°C) basis. It is assumed that the coarse fraction will retain a negligible amount of water (Richards 1965; p 136) and further assumed that water retained per g fine soil at 15 bar will not be influenced by degree of compaction.

Calculation of capillary rise from soil properties

The procedure for calculating the capillary rise of water from the water table was based on Gardner's (1958) steady-state solution to the soil water flow equation. The calculations were carried out on a daily basis. These calculations required a relationship between hydraulic conductivity, K (cm/min), and tension, h (cm water). Measurements of K were made only at saturation and it was necessary to use a predictive method for estimates of K at lower water contents and higher tensions. A procedure developed by Brooks and Corey (1964) was used for this purpose. (Orientation studies had indicated that an alternative procedure, the Millington and Quirk model (Bouwer and Jackson 1974), tended to overestimate the decrease in K with increase in tension.) The Brooks and Corey procedure was modified slightly, as described below (Eqs. 4 to 8) to allow for gas filled voids at zero tension and to accommodate the gradual decrease in water content (θ) of these undisturbed cores as tension was increased from zero to the air entry value (h_b).

Effective saturation (E_s) was calculated as:

$$Es = ((\theta/\theta_s) - S_r) / (1 - S_r) \tag{4}$$

where θ_s is the water content at zero tension and S_r is residual saturation. The value of S_r was selected so that the absolute value of the correlation coefficient between ln E_s and ln h was maximal after exclusion of the two to four points at low suction (0 and 5 cm or 0-20 cm water).The relationship ln E_s vs ln h was always non-linear at low tension.

After selecting S_r as above the moisture retention curve (MRC) can be represented by:

$$\ln E_s = \lambda \ln h_b - \lambda \ln h \quad \text{for } h > h_b \tag{5}$$

where h is tension in cm water, h_b is the air entry value and λ is a pore size distribution index. Larger values of λ indicate narrower distributions. In equivalent form Eq. 5 becomes

$$E_s = (h_b / h)^{\lambda} \tag{6}$$

Brooks and Corey (1964) found that the hydraulic conductivity (K) was represented well by

$$K = K_s \; E_s^{(2 + 3\lambda)/\lambda} \tag{7}$$

where K_s is the saturated hydraulic conductivity. The substitution of Eq. 6 into Eq. 7 for E_s gives

$$K = K_s (h_b / h)^{(2 + 3\lambda)} \qquad \text{for } h > h_b \tag{8}$$

Gardner (1958) used a three parameter equation of the form

$$K = a / (h^n + b) \tag{9}$$

Least squares estimates of the constants a, n and b of Eq. 9 were obtained by fitting K, calculated by entering Eq. 7 with E_s from Eq. 4 at the 12 h values of the MRC, into the logarithmic transform of Eq. 9, i.e.

$$\ln K = \ln a - \ln (h^n + b) \tag{10}$$

At saturation, h = 0 was replaced by an arbitrarily small value of h (usually 0.001 cm water).The constants a and b were fitted separately i.e. a/b was not set equal to K_s.

Digression

The standard Brooks and Corey model (Eq. 8 or Eq. 7 entered with E_s from Eq. 6) assumes a sharply defined air entry value with $K = K_s$ at $h < h_b$ and assumes that the constant b of Eq. 9 is zero, i.e. Eq. 9 is equivalent to Eq. 8 if

$$a = K_s\, h_b^{(2 + 3\lambda)}$$
$$n = 2 + 3\lambda$$
$$b = 0$$

In contrast, entering Eq. 7 with E_s from Eq. 4 allows K_s to decrease gradually as tension is increased from zero to h_b, consistent with the observed decrease in θ between h = 0 and $h = h_b$. This approach yielded estimates of K at h_b that were intermediate between those obtained by Eq. 8 and by the Millington and Quirk model (Bouwer and Jackson 1974).

Equation 9 was then used to calculate K at closely spaced values of h to enable numerical integration of

$$Z = \int_0^{h_{max}} dh/(1 + q/K) \tag{11}$$

(Gardner 1958) where Z is the height above a water table at which a tension of h_{max} would maintain a stead upward flux of q. Tension increments, for the j steps in this integration over the range h = 0 to $h = h_{max}$, were increased exponentially such that for a given step i,

$$h_i = h_{i-1} + P^i \quad \text{and} \tag{12}$$
$$h_{max} = h_{j-1} + P^j \tag{13}$$

j being the maximum value of i and P being some value that satisfied Eq. 13 for the given values of j and h_{max}. For integration of Eq. 11 the height above the water table (Z_i) at which the tension was hi was calculated as

$$Z_i = Z_{i-1} + (h_i - h_{i-1}) \times \{K_{i-1}/(q + K_{i-1}) + K_i/(q + K_i)\}/2 \tag{14}$$

Estimates of q for the experimental sites based on measured soil properties, water table depths and daily soil water tensions were the desired result to allow comparisons with the measured capillary rise for the several experimental periods. Equation 11, however, can not be solved explicitly for q. It was necessary to integrate for a number of q values and iterate to a value of q that satisfied h_{max} (soil moisture tension at 40 cm depth in the open cylinder) and Z (depth to water table minus 40 cm). The integration was calculated on a daily basis with j = 50. Daily values of h_{max} and Z were obtained by linear interpolation between observation dates (two to six times per week). The predicted or calculated rise was the sum of the daily q estimates over the experimental period.

Detailed calculations of Z:q relationships for the 10 sites were carried out for q values of biological interest, in order to compare the two measured sites with the remaining eight sites on which soil properties were determined. In these calculations using Eq. 11, h_{max} was set at 500 or 4000 cm water, and q was varied from 0.01 to 1.0 cm/day in 10 steps where $q_{i+1} = q_i \, 10^{0.2}$. The integrations were carried out in 500 steps (i.e. j = 500)., The resultant matrix of numeric values (10 sites x 11 flux rates x 2 h_{max}) was further simplified by fitting q vs Z for each site and each h_{max} according to

$$\ln q \text{ (cm/day)} = a' + n' \ln Z \text{ (cm)} \qquad (15).$$

The values of a' and n' were calculated by least squares estimates. For the conditions where 1 + qb/a ~ 1, (a and b are given from Eq. 9) with a and q expressed in the same units, ln q is nearly linear with ln Z and n' = -n of Eq. 9 (Gardner 1958; Eqs. 18 to 21). Note that the constants a' and n' do not apply beyond the range of q under consideration (0.01 to 1.0 cm/day). The curvature of the ln q vs ln Z relationship increases as q increases and also as q is decreased such that Z is large relative to h_{max} (Z cannot exceed h_{max} and it will approach h_{max} as q is decreased). Thus, non-linearity of ln q vs ln Z relationship occurs at extremes and beyond the range of q used.

The constants a' and n' have the advantage that they characterize capillary rise properties in a form analogous to Gardner's (1958) Eqs. 18 to 21 and express q as a function of Z. For the purposes of correlation with other soil properties such as percent sand, the coefficients a' and n' have the disadvantage that they were highly correlated (r = -0.98) with each other. In regression equations of the form $Y = c_1 + c_2X$, the degree of correlation between c_1 and c_2 will be minimal if X is replaced by $X - \overline{X}$ (Draper and Smith 1967, p 22). By reversing the variables in Eq. 15 and changing the scale in q to mm/day, mean ln q = 0 and $\ln q = \ln q - \overline{\ln q}$. Thus the relationship is written

$$\ln Z \text{ (cm)} = a'' + n'' \ln q \quad \text{(mm/day)} \qquad (16)$$

where the constants a" and n" are determined by least squares estimates and the degree of correlation between a" and n" was reduced (+ 0.67).

Equation 16 has the disadvantage that it is written with ln Z as the dependent variable when in practice ln q is the dependent variable (i.e. one is interested in the effect of Z on q and not vice versa). The correlation between ln q and ln Z over the range 0.1 to 10 mm/day is almost unity so the reversal of variables offers no problem mathematically but does imply the awkwardness of thinking backwards. The constant, a" is ln Z when q = 1 mm/day and can be related to other soil properties. This is in contrast with a' which could not be considered separately from n'.

RESULTS AND DISCUSSION

Field measurement of capillary rise

Mean capillary rise over the experimental periods in 1977 and 1979 ranged from 0.13 to 0.18 cm/day (Table 1, Fig. 3) and supplied from 45 to 79% of the water used during these periods. In view of the relatively large 95% confidence limits surrounding capillary rise measurements (Table 1) these figures (cm/day, percent of water use) are of course approximate but show that rise was a significant source of water during these periods. Water usage during these periods was 53 to 66% of Class A pan evaporation, slightly lower than would be expected under normal field conditions (80%, assuming a crop coefficient of 1 and a pan coefficient of 0.8; Doorenbos and Kassam 1979, Tables 17 and 18), perhaps because all water was supplied from below and evaporation from the soil surface would be less than normal.

The tensiometer record is also indicative of substantial capillary rise (Fig. 3). Soil moisture tension in the open cylinders fell rapidly (or increased less rapidly; site 1, 1977) following an abrupt decrease in water table depth. In 1979 the cylinders were rain-free for 14 weeks and supported a closely planted vigorous annual crop but soil moisture tension at a depth of 40 cm in the open cylinders exceeded 50 cb only briefly during this period (Fig. 3).

Water table depths were unusually low in 1978 (rainfall for the month of May was 32% of normal) and no measurement of rise was possible. Soil moisture tensions rapidly increased beyond the functional range of tensiometers (Fig. 3) and plant growth in the cylinders was very poor. This experience in 1978 is a reminder that capillary rise is a reliable source of water for plant growth only if water table depth is reliably stable within certain limits.

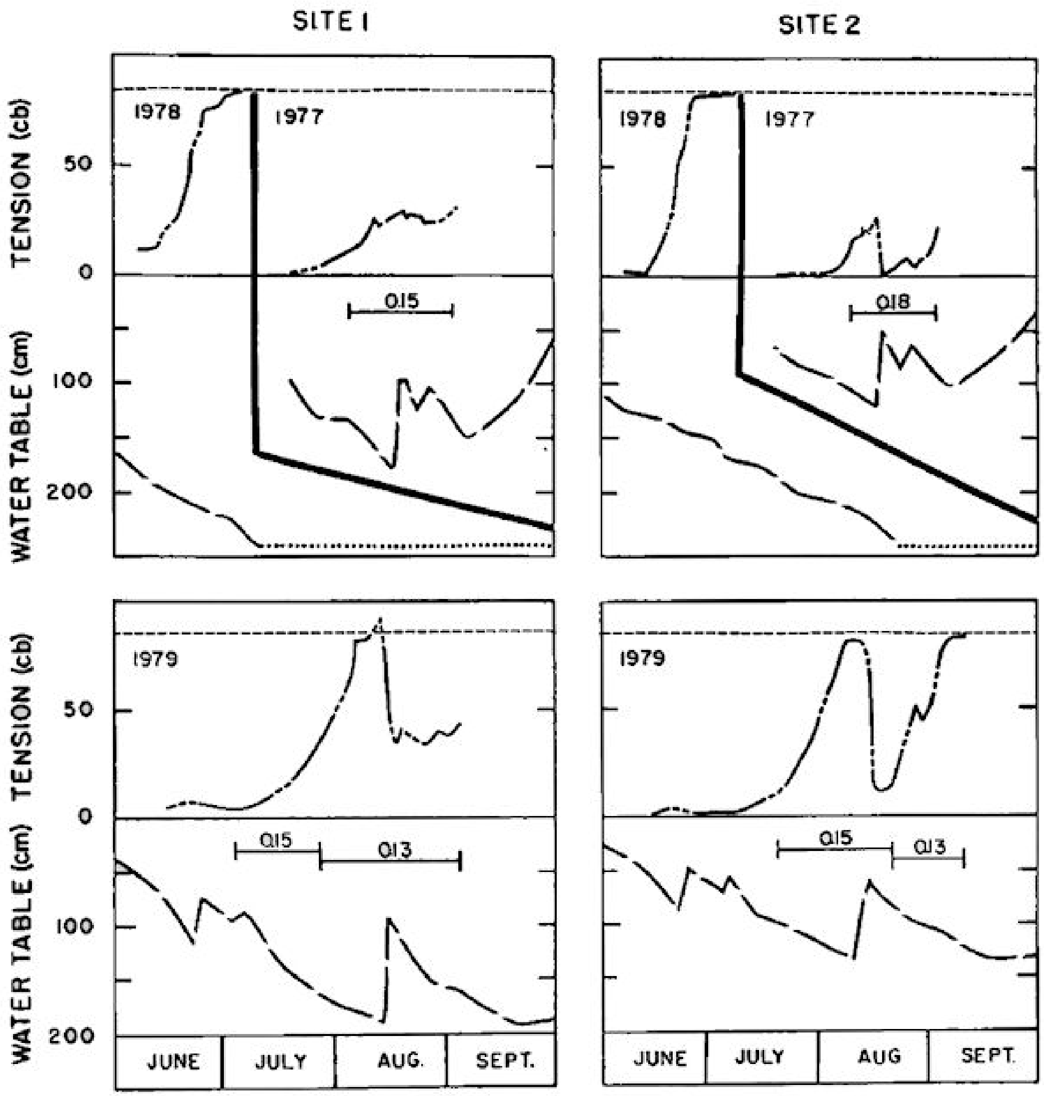

Fig. 3. Soil moisture tension in centibars at a depth of 40 cm (open cylinders) and depth to water table at sites 1 and 2 over portions of three growing seasons. Numbers within the figure are mean capillary rise (cm/day) measured over the period indicated by the underlying line.

Comparison with other sites

Having established that capillary rise can be substantial in the experimental orchard in some years it is pertinent to ask if the hydraulic properties of the subsoil in this orchard are unusually conducive to capillary rise. Tables 3 to 8 relate, directly or indirectly to this question and show that the hydraulic properties of the capillary rise sites (sample nos. 55 and 5) are not unusual but fall well within the range of core samples from the other eight sites.

Saturated hydraulic conductivity of samples from the 10 sites ranged from 1.94 to 0.0037 cm/min (Table 3) and was, for most sites, similar to K_s that would be expected on

Table 3. Moisture retention and other properties of core sample from 10 sites,

Line no.	Sample no.	9	11	8	7
1	Bulk density ± SD (g/cm^3)	1.56	1.61	1.67±0.04	1.67±0.09
2	Particle density (g/cm^3)	2.673	2.695	2.710	2.743
3	Total porosity (%)	41.6	40.3	38.4	39.1
4	Fine (%<2mm)	65.1	95.3	99.9	99.9
5	Carbon (%)	0.15	0.22	0.13	0.02
6	Sand (%2-0.05mm)	93.1	92.6	91.5	84.5
7	2-1mm (%)	25.4	11.0	5.0	0.5
8	1-0.5mm (%)	26.8	19.4	12.9	4.4
9	0.5-0.25mm (%)	17.8	23.4	25.2	10.5
10	0.25-0.1mm (%)	18.7	30.4	29.9	50.4
11	0.1-0.05mm (%)	4.4	8.4	18.6	18.7
12	Silt (% 0.05-0.002mm)	1.6	2.1	1.7	7.4
13	Clay (%<0.002mm)	5.4	5.3	6.8	8.1
	Tension (h; cm of water)	Moisture retention (θ;cm^3/cm^3)			
14	0	0.367	0.348	0.330	0.359
15	5	0.329	0.345	0.308	0.342
16	10	0.308	0.338	0.297	0.326
17	20	0.295	0.300	0.283	0.311
18	40	0.162	0.216	0.235	0.270
19	60	0.110	0.175	0.183	0.232
20	80	0.089	0.151	0.162	0.220
21	100	0.076	0.133	0.140	0.206
22	150	0.064	0.115	0.108	0.182
23	225	0.055	0.105	0.088	0.155
24	300	0.048	0.098	0.082	0.141
25	500	0.044	0.094	0.072	0.124
26	1020 (1bar)	0.038	0.086	0.066	0.110
27	15300 (15bar)	0.019	0.027	0.043	0.071
Hydraulic conductivity± SD ‡ (K_s; cm/min, saturated)		1.94	0.45	0.16±1.4	0.11±2.1
K_s predicted §		8.74	1.12	0.55	0.18

‡ Geometric mean ± antilog SD; the ± sign in this case implies multiplication and division.

§ Predicted K_s was calculated from a linear regression equation based on data of Mason *et al.* (1957,Table3) this equation being, ln K (cm/min) = -5.91 + 0.264 % air porosity at 60cm tension, over the range of 2.4 to 18.4% air porosity at 60cm tension; sites 8, 9 and 11 fell outside of this range.

Table 3. (continued)

Line no.	55	99	5	10	13	12
1	1.75±0.04	1.99±0.03	1.83±0.05	1.67±0.07	1.88±0.03	1.78±0.07
2	2.703	2.709	2.684	2.742	2.699	2.759
3	35.3	26.5	31.8	39.1	30.3	35.5
4	96.2	88.5	96.2	98.7	92.4	97.1
5	0.02	0.01	0.04	0.01	0.00	0.06
6	73.7	67.3	66.4	55.4	54.6	44.5
7	13.4	8.4	12.0	1.3	8.6	5.7
8	20.9	14.8	17.6	3.1	11.7	7.3
9	15.2	12.2	13.1	5.5	9.0	6.3
10	16.7	19.0	16.1	27.0	13.8	11.7
11	7.6	13.1	7.5	18.5	11.5	13.5
12	17.1	19.6	15.1	29.2	29.1	28.2
13	9.1	13.1	18.6	15.4	16.3	27.4
			Moisture retention (θ; cm^3/cm^3)			
14	0.320	0.284	0.324	0.357	0.299	0.349
15	0.317	0.269	0.323	0.353	0.289	0.338
16	0.302	0.260	0.317	0.345	0.281	0.337
17	0.269	0.250	0.299	0.334	0.276	0.328
18	0.232	0.231	0.272	0.312	0.258	0.319
19	0.208	0.223	0.256	0.293	0.250	0.314
20	0.202	0.217	0.249	0.277	0.244	0.310
21	0.198	0.212	0.243	0.264	0.238	0.306
22	0.192	0.205	0.235	0.247	0.232	0.300
23	0.184	0.199	0.226	0.231	0.215	0.293
24	0.179	0.195	0.220	0.219	0.221	0.289
25	0.168	0.187	0.209	0.205	0.213	0.284
26	0.154	0.176	0.197	0.188	0.199	0.272
27	0.066	0.067	0.101	0.093	0.101	0.145
	0.11±1.1	0.0051±1.20	0.025±1.7	0.020±2.4	0.0037±1.8	0.0038±2.4
	0.12	0.0082	0.014	0.036	0.011	0.0080

† Retention at 225 cm (sample 13) was considered to be in error and excluded from further analysis.

the basis of air porosity at 60 cm tension (Mason *et al.* 1957; Table 3). There was an approximately linear relationship between percent sand and ln K_s; with samples arranged in decreasing order of percent sand they were, excepting sample 99, also arranged approximately in order of decreasing K_s. Sample 99 had an unusually high bulk density.

Absolute values of the correlation coefficients between ln E_s and ln h, over the range h = 10, 20 or 40 to h = 500, approached unity (Table 4) indicating that λ and h_b (Eq. 5) adequately described the moisture retention curves of these samples. In most cases the absolute value of this correlation coefficient increased as S_r was decreased, reached a maximum value and then decreased (after excluding two to four data points at the low tension end of the moisture retention curve), this value of S_r at which a maximum was reached being the selected value of S_r.

Digression

However in two cases (samples 7 and 12) no clear maximum was reached. As S_r of sample 12 was decreased from 0.52 to 0, the correlation coefficient gradually changed from -0.9978 to reach a broad absolute maximum of -0.9979 centered on S_r = 0.13; the decrease in residuals of some points being more or less balanced by an increase in residuals of other points over the range S_r = 0.52 to S_r = 0.13.The value of S_r for sample 12 (0.52 or 0.13) had some effect on the various parameters and coefficients (Tables 4, 5, 6 and 7) but capillary rise properties were relatively unaffected within the range 0.1 to 10 mm/day (Z of Table 7). Sample 7was similar except that no maximum was reached; S_r = 0.1 being an arbitrarily small value of S_r that was compared with S_r = 0.21 in Tables 4, 5, 6 and 7. Once again the value of S_r had relatively little impact on the Z of Table 7. The values of θ_r (Table 4), for samples other than 7 and 12, fall on the MRC between 1 and 15 bar. The values of θ_r for samples 7 and 12 also fall between 1 and 15 bar, provided the larger values of S_r are used (0.21 and 0.52 respectively). These larger values of S_r for samples 7 and 12 were therefore considered preferable to the smaller values and all correlations involving the a', n', a" and n" constants of Tables 6 and 7 were entered with these variates based on S_r = 0.21 and S_r = 0.52 for samples 7 and 12 respectively.

The pore-size distribution index (λ; Table 4) tended to decrease as percent sand decreased with sample 99 being a notable exception. Note that λ is sensitive to values of S_r (Table 4, samples 7 and 12); increase in S_r leads to greater decrease in E_s over a given span of h above h_b since E_s = 1 at h = h_b and, for a value of θ corresponding to a given value of h > h_b, increase in S_r leads to decrease in E_s.

Table 4. Brooks and Corey constants (S_r, h_b and λ) and the fit of these constants to the moisture retention curve of core samples from 10 sites †.

Sample no.	S_r	θ_r	Rogued ‡	Correlation between $\ln E_s$ and $\ln h$	h_b (cm)	λ	Estimates of A	
							f §	f and OM ¶
9	0.1019	0.037	3	-0.9991	16.32	1.1512	0.33	0.41
11	0.234	0.081	3	-0.9967	18.21	0.9554	0.36	0.42
8	0.163	0.054	4	-0.9976	27.36	0.9528	0.39	0.50
7	0.21	0.075	4	-0.9944	22.17	0.5506	0.41	0.68
	0.10	0.036	3	-0.9946	15.44	0.3661		
55	0.435	0.139	2	-0.9945	8.13	0.4365	0.17	0.24
99	0.275	0.078	2	-0.9982	4.46	0.1356	0.15	0.22
10	0.46	0.149	3	-0.9988	11.04	0.2773	0.13	0.17
5	0.28	0.100	4	-0.9993	20.93	0.2834	0.17	0.25
13	0.51	0.152	3	-0.9996	8.99	0.2182	0.12	0.40
12	0.52	0.181	4	-0.9978	8.66	0.1233	0.09	0.11
	0.13	0.045	4	-0.9979	6.83	0.05743		

† See Eq. 4-6 for definition of S_r, h_b and A.

‡ Number of data points at the low tension end of the moisture retention curve that were excluded from regression Eq. 9; these first four points being 0, 5, 10 and 20 cm of water.

§ From particle size distribution (Bloemen 1980a, Eqs. 8,9, 10, 3a and 11).

¶ From particle size distribution and % carbon (Bloemen 1980a, Eqs. 8, 9, 10, 3a and 1

Note that the value selected for S_r, and therefore the value taken by λ, also influences the value taken by n of Eq. 9 (Table 5). Because Eq. 8 is an approximate description of the K:h relationship of Eq. 9 one can say,

$$K_s \, h_b^{(2+3\lambda)}/h^{(2+3\lambda)} = a/(h^n + b) \text{ and,} \tag{17}$$

$$n = 2 + 3\lambda$$

Estimates of λ obtained from particle size distribution alone (Bloemen 1980a, Eqs. 8, 9, 10, 3a and 11) and particle size distribution plus organic matter (Bloemen 1980a, Eqs. 8, 9, 10, 3a and 12) are included in Table 4 for comparison. Organic matter was assumed to contain 58% carbon (Hesse 1971, p 209). Agreement between these estimates of λ and λ obtained from the MRC was not close.

The λ values of Table 4 (obtained from MRC data) varied more with texture than would be expected on the basis of Brakensiek *et al.* (1981, Table 3) and the θ_r values of Table 4 were larger than the values of residual saturation on a fractional bulk volume basis reported by Brakensiek *et al.* for corresponding textures (1981, θ_r of Table 3).

The constants a, n and b of Eqs. 9 and 10 accounted for more than 99% of the variation in ln K, (Table 5), where K was generated for the 12 points of the moisture retention curve using λ, S_r and K_s in Eqs. 4 and 7, showing that Eq. 9 is an adequate representation of the Brooks and Corey (1964) prediction of the K:h relationships for these samples. The exponent n tended to decrease with decrease in percent sand, sample 99 again being a prominent exception.

Entering Eq. 11 with K from Eq. 9 generates the height (Z, cm) above a stable water table that is consistent with some assumed steady state upward flux (q, cm/day or mm/day) from the water table when soil moisture tension at height Z is constant and is equal to h_{max} (Fig. 4). The dashed line of Fig. 4 represents the Z:h relation at q = 0.

The regression equations of Tables 6 and 7 describe the relationships between Z and q at two values of h_{max}. Values of Z at three values of q (Table 7), as obtained directly from Eq. 11, are included for comparison with Z that can be generated using a' and n' or a" and n". For example, in Table 7 ln Z for q = 1 mm/day (col. 5) is immediately comparable to a" (col. 2). The regressions (Tables 6 and 7) are almost exactly linear within the range of q under consideration (0.01 to 1 cm/day). As noted in Materials and Methods, the coefficient n' of Eq. 15 (Table 6) approximates the exponent n of Eq. 9 (n' ~ - n). Note that these constants (a', n', a", n") do not apply beyond the range of q to which they are fitted.

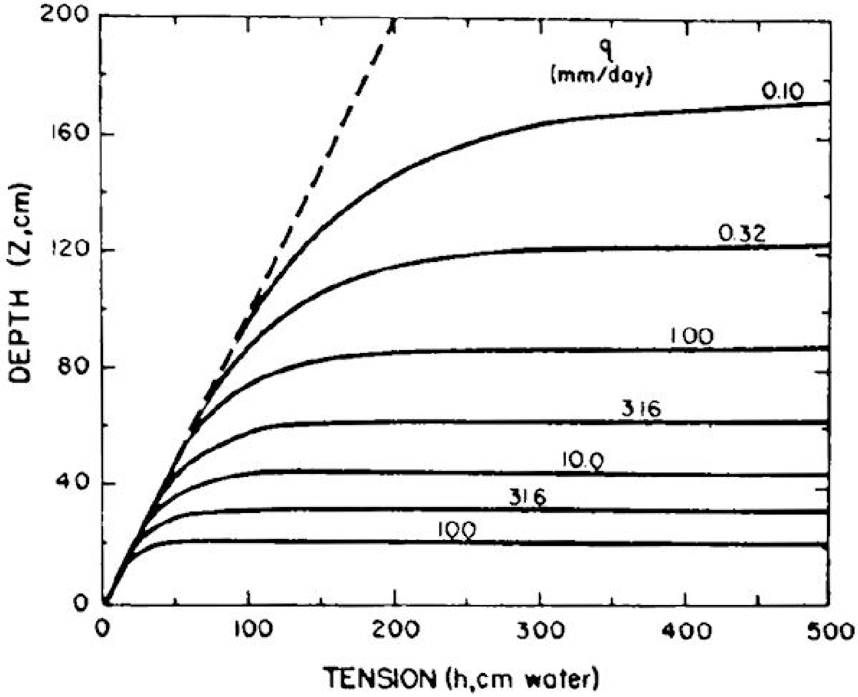

Fig. 4. Height (Z) above a stable water table and soil moisture tension (h) for selected values of steady state upward flux (q); sample no. 55.

For example, compare a' for h_{max} ~ 4000 and h_{max} = 500 (Table 6), a' being, in a literal sense, ln q at Z = 1; a' (h_{max} = 500) is larger than a' (h_{max} = 4000) which of course can not be correct. Because the a' coefficients lead to q much greater than 1 when Z = 1 they are misleading when considered in isolation.

Relations between Z and q at h_{max} = 500 cm water are more relevant to water supply and root function than at h_{max} >> 500, 500 cm water being roughly the point at which root growth becomes limited by water supply (Russell 1977, p 99). For the fitting of a linear ln q:ln Z relationship a higher h_{max} (e.g. 4000 cm water) was mathematically more desirable because the ln q:ln Z relationship was then more nearly linear (Table 6). The curvature at lower values of h_{max} arose from the constraint that Z could not exceed h_{max} no matter how small q was.

Table 5. The constants a, n and b of Eqs. 9 and 10 for core samples from 10 sites†.

Sample no.	S_r	a	n	b	Sum of squares of ln K in regression (%)
9	0.1019	11.84 $\times 10^6$	5.529	9.608 $\times 10^6$	99.8
11	0.234	1.477 $\times 10^6$	5.034	3.635 $\times 10^6$	99.8
8	0.163	2.113 $\times 10^6$	4.919	21.58 $\times 10^6$	99.7
7	0.21	9898	3.667	148670	99.3
	0.10	1346	3.275	19193	99.5
55	0.435	158.4	3.375	1356	99.3
99	0.275	0.1756	2.394	40.84	99.7
5	0.46	27.79	2.872	1071	99.9
10	0.28	124.8	2.862	7722	99.8
13	0.51	0.9143	2.589	386.2	99.4
12	0.52	0.2910	2.218	126.5	99.2
	0.13	0.1235	2.036	46.90	99.3

† Obtained by regression of ln K on h at the 12 points of the MRC (Table 3; 0-500 cm); K was generated using the constants of Table 4, the 0 of the 12 points of the MRC and K_s (Table 3).

Because the correlation between ln q and ln Z approaches unity these two regression equations (Eqs. 15 and 16) approximate algebraic equations and accordingly

$$n'' \sim 1/n' \quad '(18)$$

$$a'' \sim -(a' + \ln 10)/n' \quad \text{and} \quad (19)$$

plots of q on Z, generated using Eq. 15, are similar to plots of Z on q generated using Eq. 16.

As noted at the beginning of this section the hydraulic properties of the samples from the capillary rise sites (samples 5 and 55) are not unusually conducive to capillary rise and fall well within the range of samples from the other eight sites (Table 7). Thus the substantial capillary rise that was observed in the experimental orchard (Table 1) would probably be equalled or exceeded on many soils of the region, given comparable conditions of water table depth.

Table 6. Constants a' and n' for core samples from 10 sites and for two values of h_{max} where In q (cm/day) = a' + n' In Z (cm)†.

Core		% sand	h_{max} = 4000 cm water			h_{max} = 500 cm water		
			a'	n'	Sum of squares in regression (%)	a'	n'	Sum of squares in regression (%)
9		93.1	23.85	-5.53	100.	23.88	-5.53	99.9999
11		92.6	21.78	-5.03	99.9999	21.85	-5.04	99.9995
8		91.5	22.05	-4.89	99.999	22.23	-4.93	99.996
7	S_r= 0.21	84.5	16.84	-3.65	99.999	18.00	-3.89	99.896
	S_r= 0.1	84.5	14.93	-3.26	99.999	16.48	-3.59	99.801
55		73.7	12.80	-3.37	99.9998	12.98	-3.41	99.995
99		67.3	5.90	-2.31	99.956	5.99	-2.34	99.934
5		66.4	11.07	-2.85	99.997	11.56	-2.97	99.951
10		55.4	12.50	-2.83	99.992	14.08	-3.17	99.667
13		54.6	7.04	-2.41	99.851	7.15	-2.44	99.804
12	S_r= 0.52	44.5	6.26	-2.10	99.900	6.51	-2.18	99.792
	S_r= 0.13	44.5	5.68	-1.96	99.936	5.97	-2.06	99.816

† Values of Z, for q of 0.01 to 1.0 cm/day with $q_{i+1} = qi\ 10^{0.2}$, generated by integration of Eq. 11 with 500 tension increments between h = 0 and h = h_{max}.

Table 7. Constants a" and n" for core samples from 10 sites with h_{max} = 4000 cm water

where $\ln Z$ (cm) = a" + n" $\ln q$ (mm/day).
and values of Z at q = 10, 1 and 0.1 mm/day as obtained by numerical integration of Eq. 11.

Sample no.		a"	n"	Z(cm)		
				q=10 mm/day	q= 1mm/day	q=0.1mm/day
9		4.73	-0.181	75	114	172
11		4.79	-0.199	76	120	190
8		4.98	-0.204	90	145	231
7	S_r= 0.21	5.24	-0.274	100	190	355
	S_r= 0.1	5.28	-0.306	97	197	397
55		4.48	-0.297	45	89	176
99		3.56	-0.433	13	35	94
5		4.69	-0.351	48	110	244
10		5.23	-0.353	82	188	420
13		3.88	-0.415	18	50	123
12	S_r= 0.52	4.08	-0.476	19	60	172
	S_r= 0.13	4.07	-0.510	17	60	85

Comparison of observed with calculated capillary rise

Comparison of observed rise with rise calculated from core properties (entering Eqs. 9 and 11 with the constants a, n and b for samples 55 and 5, with h_{max} equal to soil moisture tension in the open cylinder at a depth of 40 cm and Z equal to water table depth minus 40 cm) provides a crude estimate of the quantitative accuracy of the capillary rise projections of Tables 6 and 7. Calculated and observed rise for site #1 were in good agreement (Table 8). Rise calculated for site #2 was up to eight times as large as observed rise.

Table 8. Comparison of observed capillary rise at two sites with rise calculated by numerical integration of Eq. 11 for the field conditions of daily Z (water table depth minus 40 cm) and daily h_{max} (soil moisture tension at 40 cm).

Location / Period	Observed rise (cm)		Calculated rise (cm)	
Site 1 (sample 55)				
4 Aug- 1 Sept,1957	4.3	(2.6-6.0)†	3.6	(2.5-5.1)‡
21 June- 5 July,1978	-		0.1	(0.05-0.2)
4 July- 26 July,1979	3.3	(1.7-4.9)	1.5	(1.0-2.4)
27 July- 3 Sept,1979	5.0	(3.5-6.5)	2.9	(1.9-4.4)
Site 2 (sample 5)				
9 Aug- 1 Sept,1977	4.4	(2.8-6.0)	26.7	(8.0-88.9)
21 June- 5 July,1978			1.6	(0.3-8.2)
20 July- 20 Aug,1979	4.7	(3.7-5.7)	37.4	(10.6-131.3)
21 Aug- 9 Sept,1979	2.7	(0.7-3.7)	10.1	(2.4-42.5)

† 95% confidence range, from Table 1.

‡ 95% confidence range based on rise calculated from each of four cores (see text).

The calculated rise values of Table 8 were derived from mean K_s (geometric) and mean MRC (arithmetic) of the four cores per site as described in Materials and Methods. The 95% confidence ranges of these estimates, obtained as described below, show that the cores from site #2 were much more variable than the cores from site #1. These confidence ranges were obtained by calculating rise for each of the four cores per site.

$$95\% \text{ confidence range} = C/F \text{ to } CF$$

where C is rise calculated from pooled values of K_s

$$F = \exp\,(3.182\ SD/2) \text{ and}$$

SD is the standard deviation of the natural logarithm of rise calculated from each of the four cores.

Whether the high variability of cores from site #2 reflects inherent variability within the undisturbed profile or modification of some core samples during sample extraction and processing is an open question. Whatever the cause of the high variability, it accounts in part for the discrepancy between observed and calculated rise on this site. Some possible causes of the residual disagreement between observed and calculated rise are explored in Appendix A. After adjustment for one of these causes (Appendix A) mean calculated rise on site #2 was about four times as large as observed rise and had 95% confidence limits that enclosed observed rise.

This four-fold discrepancy and the wide confidence ranges (Table 8) serve notice that the capillary rise projections of Tables 6 and 7 may be rather poor predictors of rise in the context of the intact source profile and show that some aspect of the method, perhaps soil modification during collection of cores, was unsatisfactory. Note however that these projections (Tables 6 and 7) may have a much smaller error when applied in the context of uniform profiles with properties identical to those of the core samples after collection. A four-fold discrepancy compares favourably with the error of ± two orders of magnitude discussed by Stallman and Reed (1969).

Correlations of hydraulic properties and derived parameters with other soil properties

The values of hydraulic properties (K_s in this case) and the derived parameters, such as a" and n" depend on other soil properties such as density, texture, pore size distribution, structure, etc. Both K_s and n" relate to the nature of the pore space. K_s depends most critically on the size of the largest continuous pores, whereas n" is a measure of the relative quantities of large and small pores. Thus it is possible to have n" independent of K_s. Table 9 shows, however, that for these soils n" and In K_s are highly correlated. This high correlation resulted from the fact that in these sandy soils the upper limit on pore size was similar and differences in K_s resulted from changes in pore size distribution λ or n". The direct connection between λ and n" can be seen from the following approximations:

$n \ = \ 2 + 3\lambda$ (Eq. 17)

$n' \ \sim \ -n$ (Tables 5 and 6) and

$n'' \sim 1/n'$ (Eq. 18)

from which $n'' \sim -1/(2 + 3\lambda)$ (22)

{For the samples studied here the correlation coefficient between n" and $-1/(2 + 3\lambda)$ was 0.99 and $n'' = 0.042 + 1.17\,(-1/(2 + 3\lambda))$ confirming, at least for these samples, that n" and λ are closely related and Eq. 22 is approximately correct.}

Table 9 shows that ln K_s and derived parameter, n", were both highly positively correlated with percent sand and were highly negatively correlated with D_b. These high correlations between ln K_s and other soil properties suggest that the methodological bias in K_s usually was either small or was relatively constant across samples. Percent sand and D_b accounted for 93.7% of the variation in ln K_s (Eq. 20) and 96.5% of variation in n" (Eq. 21). Equations 20 and 21 imply that, for these soils, sand content and bulk density were the dominant controls of ln K_s and n" (the shape of the moisture retention curve). The influence of other possible factors such as structure and particle size distribution within the sand fraction was apparently small. Estimates of K_s and n" obtained from Eqs.20 and 21 may be reasonably correct for soils similar to the samples under consideration but it is important to stress that Eqs. 20 and 21 can not apply to soils in general.

The parameter a" (the natural logarithm of the height, Z, above a water table or the thickness of soil across which a flux of 1 mm/day can be sustained with h_{max} = 4000 cm) was negatively correlated with bulk density, D_b. The regression relationship between a" and D_b accounted for only 64.3% of the variation in a" and, even for soils very similar to those under consideration, is a poor estimator of a". It is probable that texture and density interact to influence the value of a". The relationship between D_b and a" was shown by Boone *et al.* (1978, Fig. 8) to be first positive and then negative as soil was compacted. As the bulk density of their sandy loam Ap_2 horizon was increased from 1.33 to 1.5, exp a" increased from 33 to 144 cm and then decreased to 103 cm. The results of Boone *et al.* (1978, Figs. 8 and 9) suggest that the critical D_b in sandy loam and loamy sand, at which a" is maximum, is close to 1.4. The negative correlation between a" and D_b which we found indicates that these samples had densities above the critical value.

Table 9. Relationships between hydraulic properties and other soil properties; correlation coefficients and regression equations, where

$$\ln q \text{ (cm/day)} = a' + n' \ln Z \text{ (cm) and}$$
$$\ln Z \text{ (cm)} = a'' + n'' \ln q \text{ (mm/day)}$$

Variates	Correlation coefficients					
Sand (% fine fraction)	•					
D_b (g/cm^3)	-0.61	•				
ln K_s (cm/min)	0.90***	-0.84**	•			
a'	0.90***	-0.87***	0.95***	•		
n'	-0.92***	0.81**	-0.95***	-0.98***	•	
a"	0.47	-0.80**	0.62	0.69*	-0.55	•
n"	0.94***	-0.81**	0.96***	0.98***	-0.97***	0.67*
	sand	D_b	ln K_s	a'	n'	a"

	Correlation coefficients		
	a"	exp a"	Db
Sand	0.47	0.41	-0.61
Silt	-0.46	-0.37	0.61
Clay	-0.43	-0.41	0.54
0.5 - 0.1 mm	0.66*	0.68*	-0.56
0.5 - 0.05 mm	0.65*	0.72*	-0.47
0.25 - 0.05 mm	0.63*	0.76**	-0.34
D_b	-0.80**	-0.71*	-

Regression equations (SS = sum of squares in regression)

ln K_s = 4.58 +0.0742 % sand -7.46 D_b [$SD_{\ln K_s}$ = 0.61, SS= 93.7%, $P<0.001$] Eq. 20
n" = -0.095 +0.00417 % sand -0.302 D_b [SD_n = 0.022, SS= 96.5%, $P<0.001$] Eq. 21
exp a" = 398 +2.09 (% 0.25-0.05 mm) -208 D_b [$SD_{\exp a''}$ = 27, SS= 80.3%, $P<0.01$] Eq. 23

*P<0.05; **P<0.01; ***P<0.001.

Although the total quantity of sand was not correlated with a", the three sand fractions each had a positive correlation with a" and exp a" (Table 9). The correlation between exp a" and the 0.05 - 0.25 mm sand fraction was slightly better than with other soil fractions. A regression equation of exp a" (Eq. 23, Table 9) against the 0.05 - 0.25 mm fraction and D_b accounted for 80.3% of the variation in exp a". This tendency for exp a" to increase with an increase in fine and very fine sand content is consistent with the ability to maintain a given constant flux over greater depths of fine sand than for coarser sand (Bloemen 1980b).

In the sandy soils studied here their high density, fine sand and coarse sand contents have been shown to be the dominant properties which influence the capillary rise properties. Ranges of density and sand contents can be used to group or classify, sandy subsoils. The probable influence of the dominant properties on capillary rise can be estimated using the framework provided by Eqs. 20, 21 and 23.

For ease of visualizing the effect of the dominant properties some relevant data from other tables are drawn together in Table 10. The soils where high density, fine sand or coarse sand dominate the capillary rise are designated D, FS and CS, respectively. A fourth class, I, came out where none of these properties were dominant and the resultant capillary rise indicators had intermediate values. It is important to stress that these classes of soils are not distinct but only points on a continuum. The capillary rise indicators are exp a" (the depth of soil over which a flux of 1 mm/day can be maintained by a constant tension difference of 4000 cm), n" (an indicator of pore size distribution) and $\Delta Z/\Delta q$ for two ranges of q (i.e. the change in water table height which leads to a ten fold change in flux q).

<u>D soils</u> -

1) In soils with unusually high D_b, exp a" is small, perhaps as small as 35 cm (Eq. 23, Table 10).

2) The high Db results in small K_s (Eq. 20), low θ_s and a tendency for large θ_r. This means that there is low water yield from these soils (i.e. θ_s - θ_r is small) and the flow of water for replenishment is slow, as a result of the low K_s.

3) The constant n" is small indicating a wide pore size distribution which interacts with the low water yield and results in a great sensitivity of flux to changes in water table height e.g. ΔZ of 22 cm causes q to drop from 10 to 1 mm/day.

For a significant rise of 1 mm/day in dense sandy subsoils the water table must be shallow and stable but the low water yield and low rate of lateral down slope flow will tend

Table 10. Selected data and characteristics of the core sam arranged by type.

Type	Predominant factor	Sample number	Bulk density (g/cm^3)	Total sand (%)	Fine sand 0.25-0.05mm (%)	Coarse sand 2.0-0.25mm (%)
D	Density	99	1.99	67.3	32.1	35.4
		13	1.88	54.6	25.3	29.3
FS	Fine sand	10	1.67	55.4	45.5	9.9
		7	1.67	84.5	69.1	15.4
FS-CS		8	1.67	91.5	48.5	43.1
CS	Coarse sand	11	1.61	92.6	38.8	53.8
		9	1.56	93.1	23.1	70.0
D-I		12	1.78	44.5	25.2	19.3
I	Intermediate	55	1.75	73.7	24.3	49.5
		5	1.83	66.4	23.6	42.7

Table 10. (continued).

Type	exp a" (cm)		n"		Sensitivity ΔZ/Δq		Water yield
					$(Z_1 - Z_{10})$ § (cm)	$(Z_{0.1} - Z_1)$ § (cm)	$(\theta_s - \theta_r)$,
D	35	[51]†	-0.43	[-0.42]‡	22	59	0.206
	48	[60]	-0.42	[-0.44]	32	73	0.147
FS	187	[146]	-0.35	[-0.37]	106	232	0.257
	189	[195]	-0.27	[-0.25]	90	165	0.284
FS-CS	145	[152]	-0.20	[-0.22]	55	86	0.276
CS	120	[144]	-0.20	[-0.20]	44	70	0.267
	113	[122]	-0.18	[-0.18]	39	58	0.330
D-I	59	[80]	-0.48	[-0.45]	41	112	0.168
I	89	[85]	-0.30	[-0.32]	44	87	0.181
	109	[67]	-0.35	[-0.37]	62	134	0.175

† Values in brackets are estimates of exp a" from Eq. 23.

‡ Values in brackets are estimates of n" from Eq. 21.

§ $(Z_1 - Z_{10})$ is the change in water table depth that will decrease q from 10 mm/day to 1 mm/day and $(Z_{0.1} - Z_1)$ is the change in Z that will further decrease q to 0.1 mm/day (Table 7); the smaller the change in Z for a decade change in q the greater the sensitivity of q to Z.

Note that the rank of types is as follows:

for exp a", FS > CS > I > D,
for n", CS > FS = I > D
resultant sensitivity of q to Z is
for q > 1 mm/day FS < I = CS < D and
for q < 1 mm/day FS < I < CS= D.

to make the water table unstable. Consequently, capillary rise of water in such subsoils is unlikely to make a significant contribution to the water supply for plant growth under field conditions.

FS soils -

1) Soils with moderate D_b and in which the fine sand fraction is a major component have large exp a perhaps as large as 190 cm (Eq. 23, Table 10).
2) The values of n" are intermediate and K_s are also intermediate indicating that water removed may be replenished if an upslope source exists.
3) The flux of water is relatively the least sensitive to changes in water table height.

Of the soils considered this is the class of soils for w capillary rise is most likely to be a significant source of water. A rise of 1 mm/day can be sustained over depths approaching 2 m below the rooting zone and the flux is relatively insensitive to changes in the level of the water table.

CS Soils -

1) Sandy soils in which the coarse sand fraction dominates tend to have lower bulk density than do soils wit a wide particle size distribution. The values for exp a" are intermediate between FS and D soils (Eq. 23, Table 10).
2) The constant n" is largest for these soils as a result of the narrow pore size distribution. This leads to a high sensitivity of flux to changes in water table level, e.g. a 40 cm drop in water table would reduce q from 10 to 1 mm/da (Table 10).
3) Values of K_s will be maximum for the range of soils under consideration.

For capillary rise to be significant in these soils a relatively stable water table at intermediate depths is required.

The samples labelled I in Table 10 represent soils that are intermediate between types D, FS and CS; sandy loams of moderate D_b without predominance of fine sand and the resultant capillary rise indicator parameters are intermediate in value. Those having values intermediate between two classes are so listed in Table 10.

Influence of capillary rise on crop growth

A shallow and sufficiently stable water table would be a distinct advantage in sandy soils that have a low plant available water content when fully drained. For example, the performance of apple trees was reported to be better on imperfectly drained sandy soils than on those which were well drained (Deckers 1975). Tamasi (1964) reported better growth of 4-yr-old Jonathan apple trees in the portions of one orchard (sandy soils) with shallow water table (50-60 cm spring, 80-90 cm Aug.) than in portions with deeper water table (150 cm spring, 220 cm Aug.). All trees were sprinkler irrigated five or more times during the growing season. Over the shallow water table the trees tended to lean and to develop chlorosis but weighed 2.4 times as much as did trees on the better drained areas. Similarly, yields of irrigated corn and sugarbeet on sandy loam and loamy sand overlying sandy subsoil decreased as water table depth increased beyond the optimum depth of about 130 cm (Benz *et al.* 1981).

The present study indicates that rise is a potential source of site to site and year to year variation in the water supply for crop growth in the Atlantic region. Some rapid and reliable means of estimating capillary rise under field conditions would be desirable.

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APPENDIX A

Discrepancy between observed and calculated capillary rise at site #2 (sample 5)

The disagreement between observed and calculated rise at site #2 could have arisen in several ways. Some of these are as follows:

1) The K_s and MRC of sample 5 may be in error. Because θ_s of sample 5 is larger than total porosity (Table 3) it is probable that the MRC is somewhat in error and K_s of core samples, in particular if the soil is compact, has a large methodological uncertainty (as opposed to statistical uncertainty) arising from possible disturbance of soil during the process of core sample collection and preparation and from the unknown contribution of flow along the interface of core sample and core retaining cylinder to measured K_s.

2) The cores that constitute sample 5 may not be representative of the soil volume underlying the open cylinder. Some discrepancy between sample values and the true value of the volume sampled is to be expected.

3) The method of generating K from K_s and MRC may be inappropriate. In view of the possible errors under 1 and 2 there is no reason to conclude, at this point, that the method of generating K was inappropriate. Adjustments to the exponent in Eq. 8 have been proposed such that $2+3\lambda$ becomes $1.4+3\lambda$ (Bloemen 1980a) or $2+2\lambda$ (Russo and Bresler 1980) but these adjustments, applied to Eq. 7, would increase the disparity between observed and calculated rise.

4) The calculation of expected rise from the field records, during a rapid decrease in water table depth and during the subsequent period of shallow water table may be inaccurate due to marked departures from steady state conditions. Examination of the field records and calculations on a daily basis (Table A1) indicates that much of the discrepancy arises during these periods. The following paragraphs are directed to considering and isolating this discrepancy arising under item 4 so as to obtain a better estimate of the discrepancy arising under items 1 and 2.

First consider the increasing sensitivity of calculated steady state q to changes in soil moisture tension (h_{max}) and Z (water table depth minus 40 cm) as h_{max} and Z decrease using sample 5 as the example (Table A2). Note that tensiometer gauge error (± 20 cm at equilibrium) will introduce large errors in q only when both h_{max} and Z are small, e.g. at Z = 10 the effect of 20 cm increments in h_{max} on q is small when h_{max} > 70 cm. However at all values of h_{max} (excepting $h_{max} \sim Z$ e.g. $h_{max} < Z + 1$) q increases very rapidly as Z is decreased from 50 to 10 cm (Table A2).

Table A1. Daily values of Z and h_{max} at site 2 (1979), cumulative class A pan evaporation at the Kentville weather station and cumulative rise as calculated from sample 5.

		Z (cm)	h_{max} (cm water)	λ (cm)	Calculated rise † (cm)
July	20*	51.5	95	0.56	0.61
	21	55.1	125	1.14	1.18
	22	58.8	155	1.62	1.68
	23	62.4	182.5	2.24	2.12
	24*	66.0	210	2.72	2.50
	25	68.0	245	3.06	2.86
	26*	70.0	280	3.62	3.20
	27	71.3	301.5	3.94	3.52
	28	72.0	323.5	4.22	3.84
	29*	73.5	345	4.84	4.14
	30	73.8	412.5	5.32	4.44
	31*	74.0	480	5.86	4.74
Aug	1	77.5	510	6.14	5.00
	2*	81.0	540	6.38	5.23
	3	82.0	592.5	6.73	5.46
	4	83.0	645	7.07	5.68
	5	84.0	705	7.63	5.89
	6*	85.0	765	8.25	6.09
	7	86.4	787.5	8.59	6.29
	8*	87.8	810	8.69	6.48
	9	90.2	815	9.35	6.65
	10*	92.8	820	9.55	6.81
	11	72.0	808.5	-	7.14
	12	51.0	797	10.16	8.01
	13*	30.0	785	10.34	11.56
	14	25.5	507.5	10.64	16.80
	15*	21.0	125	11.12	24.66
	16	27.0	112.5	11.66	28.96
	17*	33.0	100	12.14	31.44
	18	34.0	110	12.38	33.77
	19*	35.0	120	12.48	35.96
	20	40.5	135	12.58	37.44

Z = Water table depth minus 40.
h_{max} = Soil moisture tension at a depth of 40 cm.
λ = Cumulative Class A pan evaporation.
† Cumulative daily rise calculated from properties of sample 5 assuming Z and h_{max} are constant over each day.
* Dates of observation; major rain events were 16 mm 10 Aug and 39.7 mm 12 Aug.

Table A2. Flux in cm/day for sample 5 at selected values of Z and h_{max}, where h_{max} is the constant tension imposed at a height Z above a water table.

h_{max} (cm water)	Flux(cm/day)									
Z (cm)	10	20	30	40	50	60	70	80	90	100
Z +0.01	.027	.007	.002	.0007	.0004	.0002	.0001	.00006	.00004	.00004
Z +0.1	.27	.068	.020	.007	.004	.002	.001	.0006	.0004	.0002
Z +1	2.7	.68	.20	.076	.034	.017	.010	.006	.004	.002
Z+ 10	19.6	4.8	1.5	.61	.29	.15	.09	.05	.03	.02
Z + 20	26.0	6.6	2.2	.94	.46	.25	.15	.09	.06	.04
Z + 40	29.5	7.9	2.9	1.3	.64	.36	.22	.14	.09	.06
Z + 60	30.6	8.4	3.1	1.4	.74	.42	.26	.17	.11	.08
Z + 80	31.0	8.6	3.3	1.5	.79	.45	.28	.19	.13	.09
Z +100	31.2	8.7	3.3	1.5	.82	.48	.30	.20	.14	.10
Z + 200	31.6	8.9	3.5	1.6	.88	.53	.34	.23	.16	.12
Z + 300	31.7	9.0	3.5	1.7	.90	.54	.35	.24	.17	.12
Z + 400	31.8	9.0	3.5	1.7	.91	.55	.35	.24	.17	.13
Z + 500	31.8	9.0	3.5	1.7	.92	.55	.35	.24	.17	.13
500	31.8	9.0	3.5	1.7	.91	.55	.35	.24	.17	.13
4000	31.9	9.1	3.6	1.7	.93	.56	.36	.25	.18	.13

Errors in measured $_{hmax,}$ due to higher root densities near tensiometer tips, could lead to large errors in calculated rise when Z is small. For example, with Z = 20, true h_{max} of 21 and measured h_{max} of 100, the corresponding fluxes are 0.68 and 8.6 cm/day respectively (Table A2).

Recall that the calculations of rise (Table 8), from core properties using Eq. 11, are valid only to the extent that q is in equilibrium with an h_{max} and Z that remain constant over each 24-hr period and, with this in mind, consider the relevance of these steady state assumptions to two conditions; Z = 90 and Z = 20 with particular reference to the first run on site 2 in 1979 (Table A1) and Table A2. As Z increased from 51 to 93 cm, daytime soil moisture tension gradually increased (Table A1), i.e. daily rise was less than daily usage. Because most water usage would occur during daylight hours and rise would occur throughout the 24-hr period (given sufficient tension) there will be some diurnal oscillation in tension but no great diurnal oscillation in flux at Z = 90 and daytime h = 500 (lower right hand corner of Table A2). At a sufficiently large value of Z the assumptions of constant flux in equilibrium with a constant value of h over the period of 1 day are approximated. Now suppose Z is suddenly decreased to 20 cm and assume, for immediate purposes, that Table A2 describes the dependence of q on h_{max} and Z at site 2 exactly. Table A2 says that, given h_{max}= 500 cm water, flux will be 9.0 cm/day. Such a projection is of course meaningless in the field conditions under consideration because steady state relationships between q, h_{max} and Z will not apply until h_{max} and tension:depth relationships have gradually become readjusted to the new water table depth. Further, at a sufficiently small value of Z and with most water usage during daylight hours, diurnal oscillations in h_{max} and q (and probably Z; Jaworski 1969) can be expected and a steady state condition is not likely to be approximated.

Estimates of rise, excluding these periods of shallow water table can be calculated as follows:

> Using the first run in 1979 as an example (Table A1), evapotranspiration for the period 20 July to 10 Aug can be calculated from class A pan evaporation records by assuming that the ratio of evapotranspiration to pan evaporation remains constant over the period of the run. Because the ground cover was well established before the start of the run (Table 1) and experienced only moderate moisture stress (Fig. 3) the error arising from this assumption is likely very small relative to the discrepancy under consideration.

$$EV_0\ (t_1) = [EV_c\ (t_2) / A\ (t_2)]\ A\ (t_1),$$

where t_1 = 20 July to 10 Aug, t_2 = 20 July to 20 Aug, EV is evapotranspiration, A is class A pan evaporation and the subscripts o and c refer to open and closed cylinders respectively.

From Tables 1 and A1,

$$EV_0\ (t_1) = (8.35/12.58) \times 9.55$$

$$= 6.34 \text{ cm.}$$

Soil moisture tensions on 10 Aug and 10 Sept were similar (Fig. 3). Therefore water contents (W_0) will be similar, and

$$W_{o\ (10\ Aug)} = W_{o\ (10\ Sept)}$$

$$= 7.26 \text{ cm (Table 1).}$$

The accumulated deficit (D) for the period 20 July to 10 Aug will then be,

$$D = W_{o\ 20\ July} - W_{o\ 10\ Aug}$$

$$= 11.80-7.26$$

$$= 4.54$$

and

$$\text{Rise (20 July to 10 Aug)} = EV_0 - D$$

$$= 6.34-4.54 = 1.80 \text{ cm.}$$

For this same period a rise of 6.81 cm was projected by sample 5. On this basis sample 5 is therefore in error by a factor of 6.81/1.8 = 3.8 (Table A3). A similar calculation for the 1977 run for the period 9 Aug to 16 Aug leads to an error factor of 4.0. The error factor for the second run on site 2 in 1979 is 3.7 (Table A3).

Therefore the combined effect of 1 or 2 (errors in measurement of K_s and MRC and departure of sample 5 from profile properties at site #2) leads to estimates of rise that are approximately four times too large. Note however that this lack of agreement is a reflection of variability in measurements and is not a firm contradiction; the values of observed rise fell within the 95% confidence limits of calculated rise (Table A3).

Tensiometer tips were positioned in disturbed soil (mean D_b of 1.45 g/cm^3 at 40-50 cm depth at site #2), 10 cm above the undisturbed subsoil (mean D_b 1.83 g/cm^3), whereas a uniform profile of undisturbed subsoil was assumed in the calculations in the belief that the error introduced by this simplifying assumption would be small relative to other errors under field conditions.

Table A3. Comparison of observed and calculated capillary rise at site #2 (sample 5) over periods free of unusually high water table.

Period	Observed rise (cm)	Calculated rise (cm)		Error (Calc./Obs.)
9 Aug- 16 Aug, 1977	0.6	2.4	(0.6 - 10.4)†	4.0
20 July- 10 Aug, 1979	1.8	6.8	(1.6 - 29.6)	3.8
21 Aug- 9 Sept, 1979	2.7	10.1	(2.4 - 42.5)	3.7

† 95% confidence range based on rise calculated from each of four cores.

One may speculate that calculated rise was larger than observed rise at site #2 because the disturbed soil was less favourable for capillary rise. To examine this possibility, K_s and a MRC were measured on a core that was reconstituted at a D_b of 1.47 g/cm^3 using soil from this site. The indicated consequences of this layered situation were small and, over most combinations of h and q, were in the opposite direction, i.e. more favourable for capillary rise (Table A4). The constants a, n and b (Eq. 9) for the disturbed core were 2.359 x 10^5, 4.568 and 3.366 x 10^6 respectively, quite different from the comparable constants of the undisturbed cores (Table 5, sample 5) and led to appreciably larger values of Z in profiles assumed to be disturbed throughout (Table A4).

However, replacing the upper 10 cm of undisturbed soil with disturbed soil had relatively little effect on Z in these simulations (Table A4).

Table A4. Height above a water table (Z) at which a tension of h_{max} would lead to a flux of q for three assumed profile conditions at site #2 (sample 5).

h_{max} (cm water)	q=1cm/day			q=0.1cm/day		
	500	100	20	500	100	20
	Z (cm)					
Assumed profile						
Sample 5, undisturbed	48.3	44.7	18.86	107.8	78.9	19.88
Sample 5, disturbed	79.3	72.9	19.79	132.0	93.9	19.98
10cm sample 5 dist. over sample 5 undist.	53.5	51.7	19.59	105.9†	82.8	19.96

† At h_{max} = 500 cm and q = 0.165 cm/day the undisturbed and layered profile simulations were equivalent, i.e. Z = 91 cm in undisturbed soil and Z = 91 cm in the layered profile composed of 10 cm disturbed soil over 81 cm of undisturbed. At Z > 91 cm the layered profile is slightly less favourable to rise.

LIST OF FIGURES

LIST OF TABLES

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LIST OF COMMON SYMBOLS

h	Soil moisture tension (cm water).
h_b	Air entry value; see Eq. 5 (cm water).
θ	Soil water content (fraction of soil bulk volume; cm^3/cm^3).
θ_s	Soil water content measured at h = zero; i.e. not set equal to total porosity (cm^3/cm^3).
S_r	Residual saturation (= θ_r / θ_s).
θ_r	Soil water content considered to be non-mobile; $\theta_r = S_r \theta_s$.
E_s	Effective saturation; see Eq. 4 (mobile water expresses as a fraction of unity).
K	Hydraulic conductivity (cm/min).
K_s	Saturated hydraulic conductivity (cm/min).
q	Flux, positive upward (cm/day or mm/day).
Z	Height above a water table to some reference point (cm).
D_b	Dry bulk density (g/cm^3).
MRC	Moisture retention curve; measured values of θ over a series of h values.
a, n and b;	Constants of Eqs. 9 and 10.
a' and n';	Constants of Eq. 15
a" and n";	Constants of Eq. 16
exp a";	From Eq. 16; the height Z (cm) over which a flux of 1 mm/day can be sustained by a constant tension of 4000 cm.