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EVALUATION OF CRITICAL SOIL PROPERTIES NEEDED TO PREDICT SOIL WATER FLOW UNDER DESERT CONDITIONS

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ABSTRACT

Hydraulic conductivity and soil-water diffusivity have been measured for a desert soil over a suction range of 0 to -50 bars, using a transient outflow method. The work was carried out in the laboratory on soil cores, both artificially packed and taken from the field. Results show good agreement between experimental and calculated conductivity values, except at the higher soil suctions (>-6 bars). At these suctions, experimental values appear to be too high. Several reasons for this divergence are given. The most likely of these is increased fluxes due to a temperature gradient. The latter would be caused by the cooling effect of the water evaporating at the soil surface. Experimental evidence is needed to ascertain this hypothesis.

Future work will assess the contribution of temperature gradients to soil water movement and quantify the transmission coefficient associated with these gradients. These data will be combined into the proposed model to estimate water withdrawal patterns from desert soils.

INTRODUCTION

Biological activity and productivity in desert ecosystems are largely dependent upon water supply. To achieve the stated goals of the Desert Biome, a predictive model for estimating patterns of water withdrawal from soil as a function of depth and time was proposed. In order for such a model to be tested, soil water transfer properties as functions of depth and water content need to be determined.

In soil systems, water flows in response to hydraulic head, temperature and osmotic gradients. Each of these driving forces is associated with a transmission coefficient which must be evaluated before field measurements of gradients can be used to compute water movement in soil.

Under desert conditions, soil water potentials are well below -1 bar during most of the year. (See Qashu, 1972, and Wheeler, 1972). So far, little work has been done in characterizing water flow properties through soil at these low water contents. Existing methods relate to agricultural lands under irrigated conditions, so that they must be expanded to encompass the range of water contents or potentials found in a desert environment. A method to evaluate hydraulic conductivity and soil water diffusivity was tested in which soil psychrometers were used where previously tensiometers had been used. Unfortunately, psychrometers do not function with any degree of reliability below a water potential of -50 bars. Much lower potentials are encountered in the warm desert soils, especially in the surface layers. Therefore, other methods will have to be developed.

OBJECTIVES

The overall objective to this study was to develop and test under field conditions a theoretical model for predicting water withdrawal patterns from soil as a function of depth and time in the presence or absence of plant roots under desert conditions. The objectives given in the project proposal were revised as a result of discussions with R. J. Hanks to include basic soil water transfer properties as determined in the laboratory. It was concluded that these functions were not well known for the soils of the Desert Biome Validation Sites. The specific objectives of the research conducted during 1972 were:

1. To determine soil moisture characteristic curves or water content as a function of matric potential.
2. To evaluate hydraulic conductivity and soil water diffusivity as a function of matric potential or water content in the dry range.

3. To determine liquid and vapor phase fluxes of soil water.

METHODS

Sampling and physical properties

Soil samples were collected (to a depth of 1 m) from the Santa Rita Experiment Range in Tucson, Arizona, and from the Rock Valley, Nevada, site (to a depth of 50 cm). The samples included loose fragments, monoliths and undisturbed soil cores of various lengths and diameters. As of this writing, no work has been performed on the Rock Valley samples because of the difficulties encountered in receiving permission from A.E.C. to enter the site and bring samples back to the laboratory. All the work reported hereafter pertains to the Sonoran Desert soil (Sonoita series).

The less than 2 mm fraction of the soil was analyzed for particle size distribution and was found to be of sandy loam texture (63% sand, 20% silt and 17% clay). Bulk densities were determined in the field by the rubber balloon method and in the laboratory by the clod and core methods (Blake, 1965). Results are given in Table 1. The values are high due to approximately 20% of the particles being larger than 1 mm in diameter. Saturated hydraulic conductivity was measured at 1.5 cm hr^{-1} on the small soil cores. The electrical conductivity of the saturation extract was 0.55 mmhos cm^{-1} while the saturated water content was found to be 26.2% on a dry weight basis.

Table 1. Bulk density of Sonoita sandy loam

Sample	Depth cm	Sample Weight g	Bulk Density g cm^{-3}
Field test	0 - 15	3090	1.79
5-cm cores	2 - 7	162	1.79
	10 - 15	157	1.73
3-cm core	2 - 32	3890	1.60
Soil clods	0 - 20	85	1.83
	20 - 50	134	1.81
	50 - 95	92	1.82
Average			1.77

Transfer properties

Soil water flux in one dimension is described by the Darcy equation

$$v_z = K_z + K_z \left(\frac{\partial h}{\partial z}\right) \qquad (1)$$

where K_z is the hydraulic conductivity of the soil in the vertical direction at depth z (z = 0 at the surface), and h is the soil water matric suction, defined here as positive in unsaturated soil. For the horizontal case

$$v_x = K_x \left(\frac{\partial h}{\partial x}\right) \tag{2}$$

Equations (1) and (2) consider water fluxes due only to matric suction gradients. Fluxes due to osmotic and temperature gradients may be combined with equation (2) to give

$$v_x = K\left(\nabla H + \frac{L_{wD}}{K}\nabla\pi - \frac{L_{wq}}{K}\nabla T\right)_x \tag{3}$$

where ∇H, $\nabla\pi$, and ∇T are the hydraulic head, osmotic pressure, and temperature gradients respectively; L_{wD} is the conductivity associated with water transfer due to salt concentration gradients, and L_{wq} represents the effect of the temperature gradient on water transfer in the vapor and liquid phases.

Hydraulic conductivity (K) was measured under isothermal conditions (24 ± 1 C) on 30-cm length of 10-cm diameter cores by a transient flow method modified from that of Weeks and Richards (1967)*. At first, water was withdrawn from one end of the column through a hollow ceramic cell under controlled suction. But as the column dried out, the ceramic cell was removed and the water allowed to evaporate freely into the ambient atmosphere, while the tensiometers, which were inserted at four different distances from the end at which water was withdrawn, were replaced by soil psychrometers as they went off scale. The soil psychrometers had been previously calibrated in potassium chloride solutions at 25 C according to the procedures outlined by Wiebe et al. (1971). The volume of outflow was measured by a burette attached to the ceramic cell and by weighings of the entire apparatus when the column was evaporating. The volume of outflow and the four suctions were recorded periodically. It was estimated that, for this soil at least, the osmotic pressure component, as measured by the psychrometers, was negligible since the electrical conductivity of the saturated extract was so low. Letey (1968) has concluded that the value of the coefficient L_{wD} was relatively low in all soil systems, although it may approach the value of K as the soil suction increases.

Two soil cores were used. One column (Column 1) was packed in the laboratory with loose soil from the 0 to 20 cm depth at an average bulk density of 1.4 g cm^{-3}. It was later found that this value was too low, as shown in Table 1. Only the tensiometer range was covered in this trial. The second column (Column 2) was taken in the field from the 2 to 32 cm depth. Its average bulk density was calculated at 1.6 g cm^{-3}. The suction at 2.5 cm from the drying end of the column reached -50 bars at the end of the experiment. After the run was completed, the field core was sectioned into 1 cm lengths and water contents were determined gravimetrically.

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* Their equation (6) should read. . . . $(1 + n_t b_j)$ instead of $(1 \times n_t b_j)$.

Calculation of hydraulic conductivity and soil water diffusivity were carried out on an IBM 360/50 Data Processing System using a program written in Fortran IV. This program yields as intermediary results values of volumetric water content as a function of matric suction. These variables are assumed to be related by an equation of the form

$$\theta\ (h) = ah^{-b} \qquad (4)$$

In this equation, the constants a and b are calculated by the least squares method taking logarithms of both sides of equation (4) (h is expressed in cm of water or millibars). The relation between K and h is represented by

$$K(h) = ch^{-d} \qquad (5)$$

where K(h) is expressed in cm hr^{-1} in cm of water, and c and d are empirical constants calculated by the least squares method from the logarithmic form of the equation. Diffusivity is related to hydraulic conductivity by the following equation

$$D_{x,t} = K_{x,t}\ \left|\left(\frac{\partial h}{\partial \theta}\right)_{x,t}\right| \qquad (6)$$

The reciprocal of $|\ (\partial h/\partial \theta)_{x,t}|$ is the differential water capacity ($C_{x,t}$), which can be calculated from the derivative of equatrion (4) using a numerical differentiating subroutine in the program mentioned above.

RESULTS

The moisture characteristic curves for the two columns for desorption are given in Figure 1. Data points correspond to experimentally determined values. The lines correspond to values calculated from the transient flow method according to equation (4). Gravimetric water contents were obtained by dividing θ by the bulk density. These curves are compared with data from Wheeler (1972) using the desorption isotherm he obtained for a soil sample from the same study site at a depth of 35 to 43 cm. An equation was fitted to these data taking logarithms of both variables and applying the linear least squares technique. It must be noted that the moisture characteristic curve for Column 1 is extrapolated from data covering only the -0.03 to -1 bar range. No attempt was made to investigate hysteresis of the water content-suction curves. Wheeler (1972) has shown that hysteresis for this soil is quite small.

Unsaturated hydraulic conductivity values calculated from Column 1 over the suction range -0.03 to -1 bar are shown in Figure 2. The same range is covered in Figure 3 for Column 2, whereas values covering the range -0.03 to -50 bars suction for Column 2 are given in Figure 4. The experimental points for K as a function of h for three positions along the column are shown. Again, the straight line represents the least squares logarithmic equation which can be written in the form of equation (5). The comparison of individual values of K in Figures 2 through 4 and values computed from equation (5) show that 39% of the 180 relative error values are less than 30%; 71% of these values are less than 50%. The agreement is much better if only Figures 2 and 3, covering the tensiometer range of soil suction, are compared.

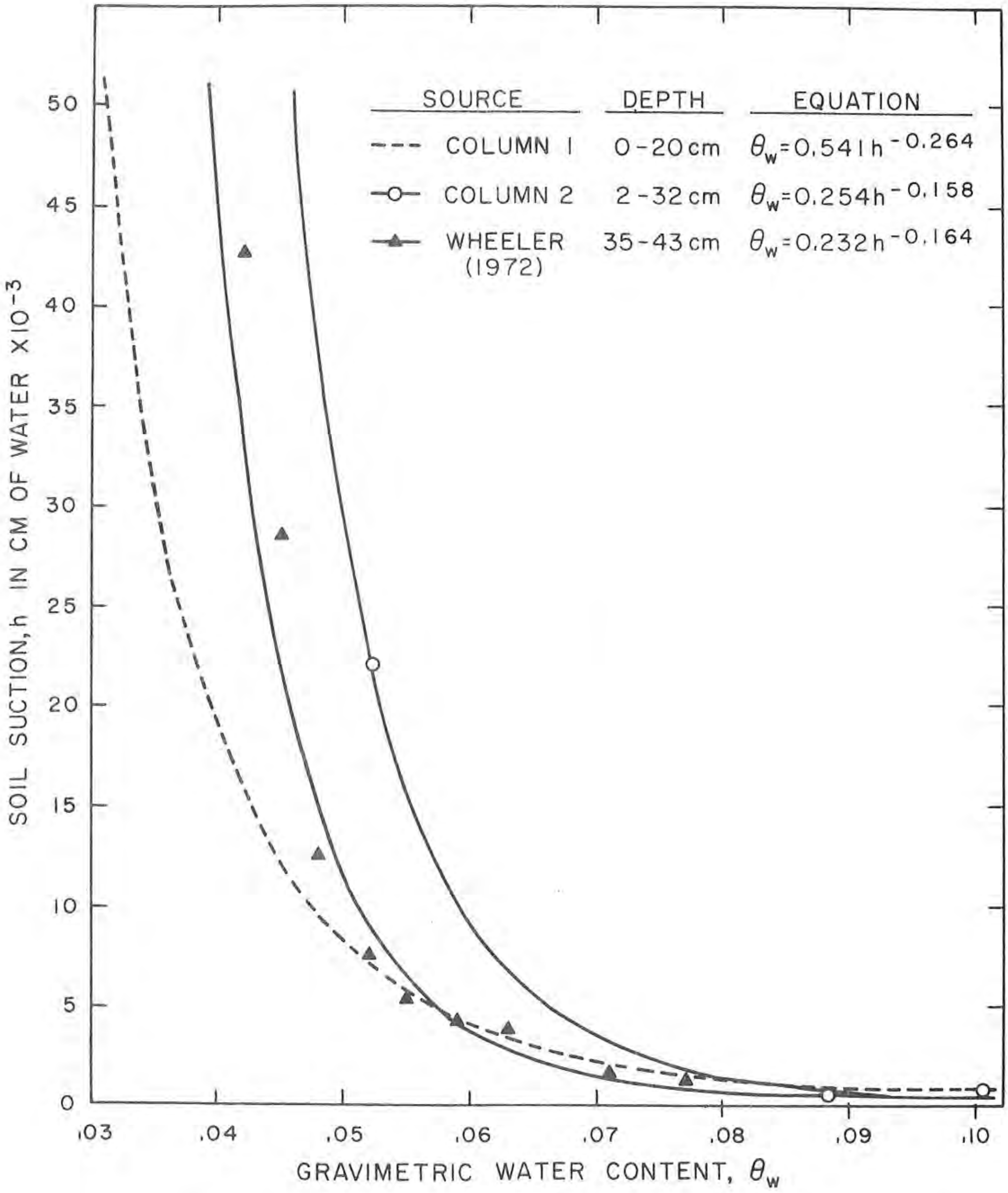

Figure 1. Gravimetric water content (θ_w) as a function of soil matric suction (h) during desorption of Sonoita sandy loam.

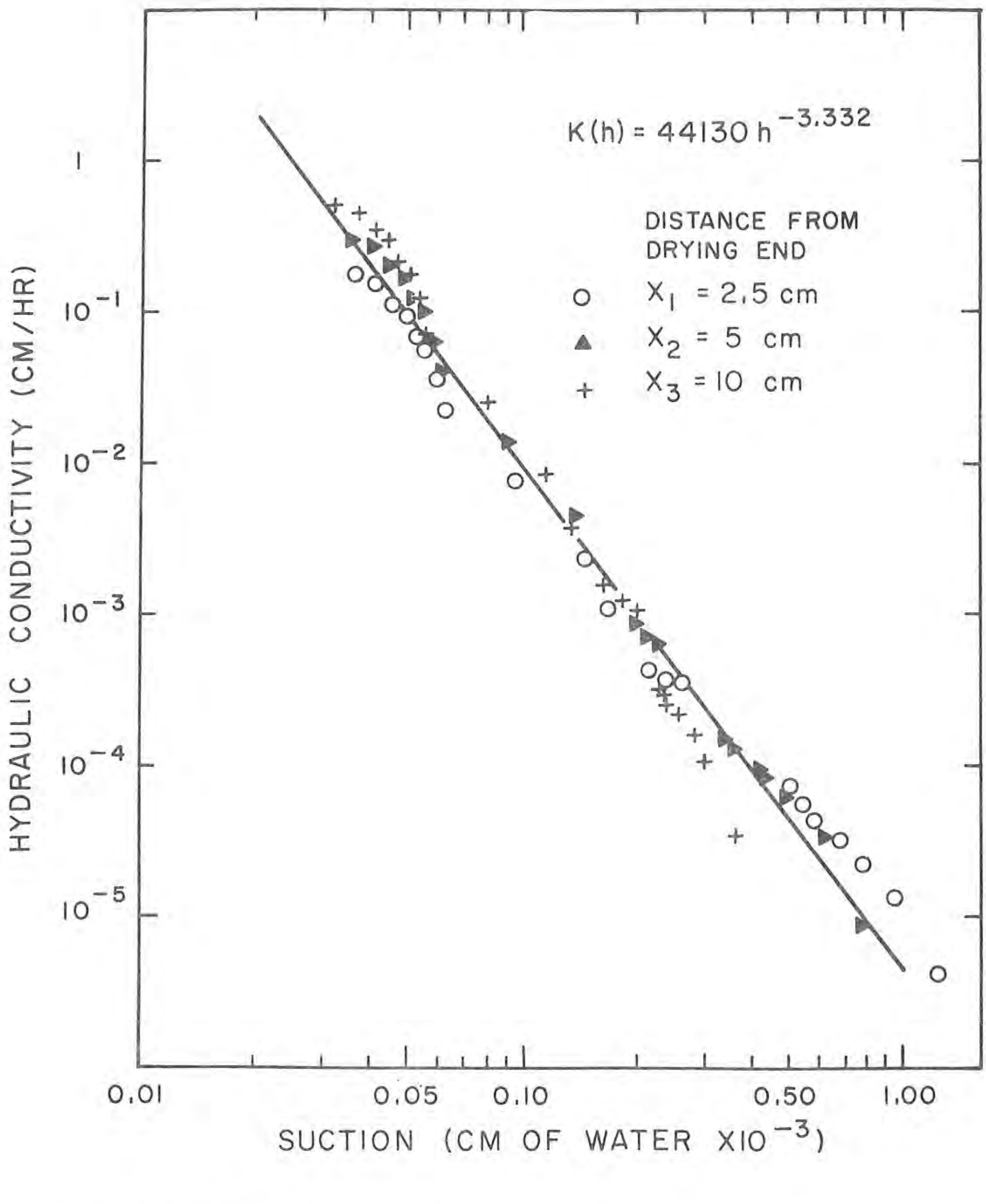

Figure 2. Experimental points given for hydraulic conductivity at three locations and plotted as a function of matric suction for Column 1.

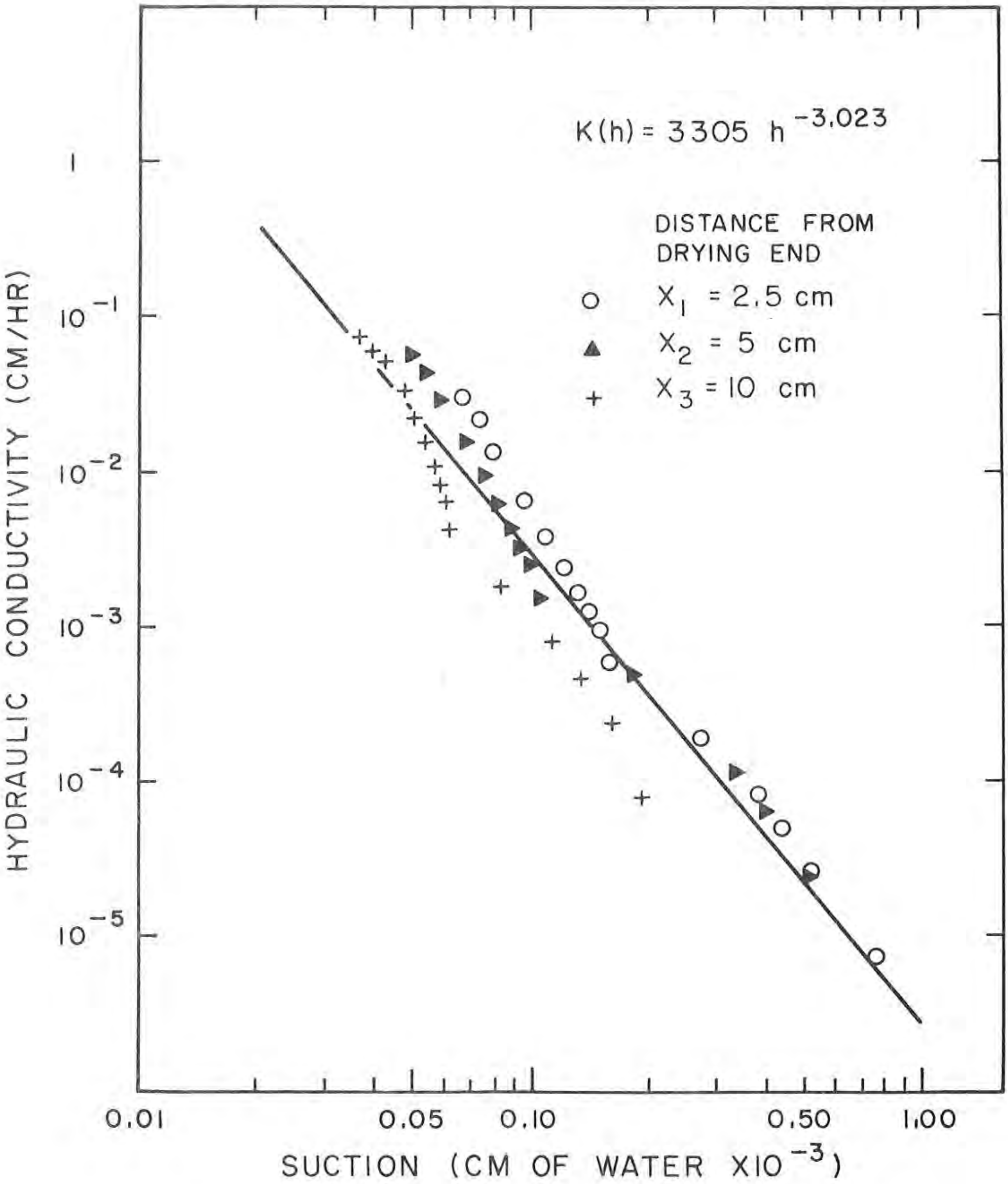

Figure 3. Experimental points given for hydraulic conductivity at three locations and plotted as a function of matric suction for Column 2. Data cover only the tensiometer range.

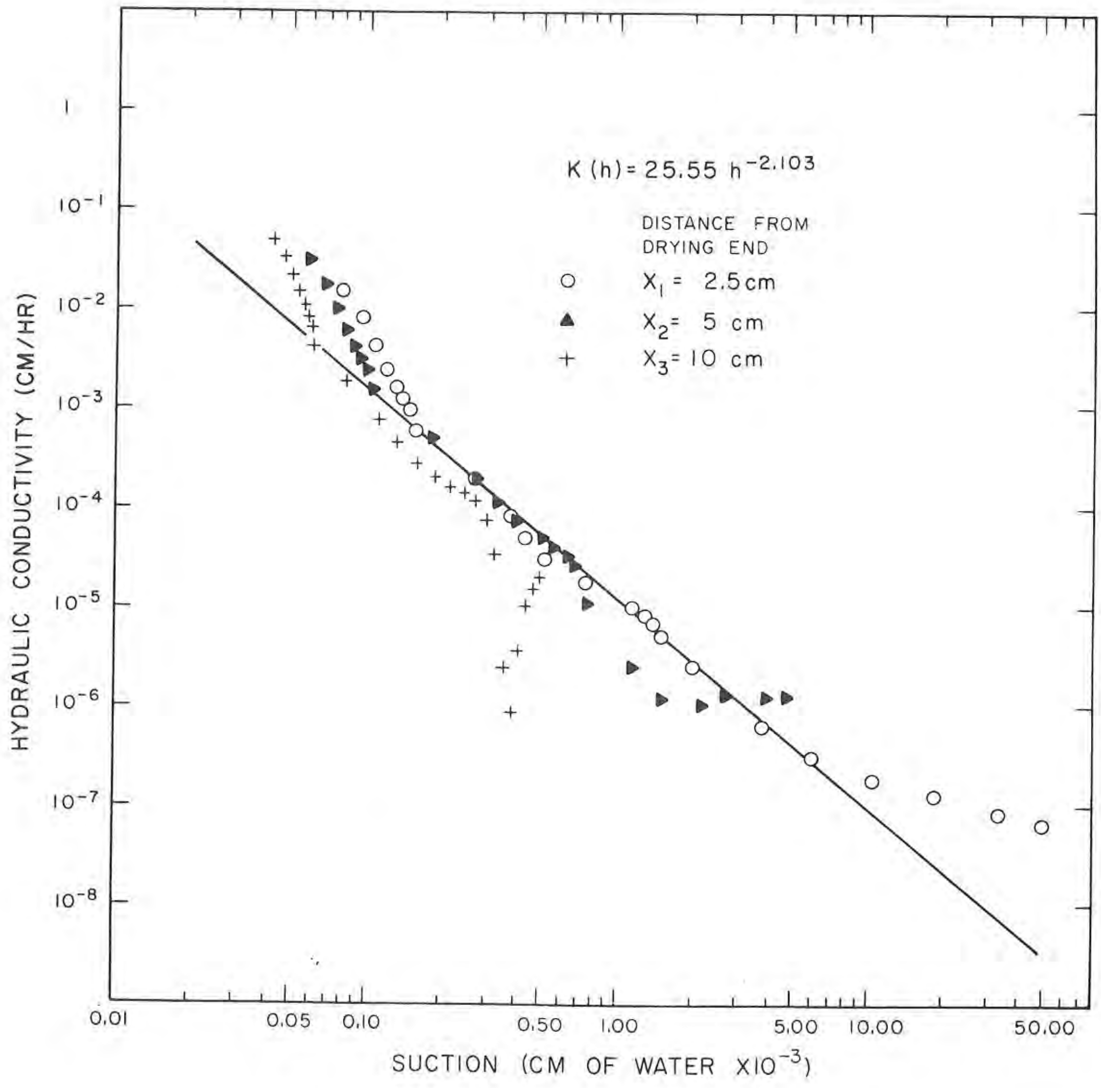

Figure 4. Hydraulic conductivity plotted for matric suctions up to -50 bars for Column 2.

Weeks and Richards' method assumes the relationship between suction (h) and distance (x) from the drying end of the column to obey an exponential function represented by

$$h(x)_t = m_t\, x^{-nt}\ ,\ x > 0 \tag{7}$$

at any time (t) greater than zero. The greater disparity noted in Figure 4 can be attributed to the fact that in the drier range (h >-5 bars) this relationship does not hold. Reasons for this will be given in the discussion section.

DISCUSSION

The water characteristic curve for desorption (Figure 1) obtained experimentally by Wheeler (1972) is in close agreement with the curve calculated from Column 2. Better agreement still might have been obtained had the soil samples been for the same depth. Wheeler's data show that a shift of these curves towards lower water contents occurs with increasing depth in the profile, due to decreasing clay content as the depth increases. The equation obtained from Column 1 diverges most. This may be the result of extrapolation to -50 bars suction from data covering only the tensiometer range.

The general agreement between experimental and calculated conductivity values is good. Examination of Figure 4 suggests, however, that perhaps two equations, for the wet and dry portions respectively, would fit the data points better. Above -6 bars suction, the experimental points tend to lie consistently above the calculated curve. Several reasons for this may be pointed out.

First, as mentioned earlier, equation (7) is not obeyed at these higher suctions. Suctions calculated from this set of equations at the first position along the column (x_1 = 2.5 cm) would be somewhat lower than the measured values. The experimental K values would then fall closer to the calculated line.

Second, it was thought that vapor phase fluxes might contribute increasingly to the total flux of water at higher suctions. However, calculations of the water flux due to vapor diffusion alone, at a point in the column 2.5 cm from the drying end where suction was -50 bars, accounted for only 4% of the total flow. However, the same calculations carried out at the plane x = 1 cm, for which gravimetric water content was 0.03 (determined at the end of the experiment), showed that all the flux was in the vapor phase. The diffusion coefficient for vapor was found to be 2.51 x 10^{-5} cm^2 sec^{-1}, a value that correlates well with the work of Jackson (1964 and 1965) on Pachappa loam. Rose (1963) and Philip and De Vries (1957) have estimated that liquid flow ceases at a water content corresponding to about 0.6% relative humidity.

This value in turn would correspond to a suction of -700 bars at 24 C and to a gravimetric water content of 0.03% for the Sonoita soil.

A third possibility, and probably the most likely, is that a temperature gradient across the first few centimeters of the column may have occurred due to the cooling effect of the water evaporating at the surface of the soil. During studies unrelated to the present project, soil water flowed upward in a vertical column evaporating at its surface, while the hydraulic head gradient was zero. Therefore, in this study also, the flux could have increased while the hydraulic head gradient remained constant. And, since K was calculated as the ratio of the flux over the hydraulic head gradient, this would provide an explanation of why experimental K values were higher than calculated values. However, temperatures were not monitored during this experiment, leaving this hypothesis to be verified.

EXPECTATIONS

The research conducted in 1972 yielded data on the water transfer properties of the Santa Rita Experiment Range soils. Similar data will be collected for the Rock Valley soils.

Experiments will be conducted to characterize the fluxes due to temperature gradients for both the Sonoran and the Mohave desert soils. Because commercially available soil psychrometers unfortunately go off scale at about -50 bars pressure, and because it is too time-consuming to construct one's own, diffusion type experiments will be conducted to investigate moisture movement at soil water contents corresponding to pressures greater than -50 bars.

These results combined with those reported here will be used to test the model described in this study's proposal.

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