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HYDRAULIC CONDUCTIVITY FUNCTIONS DERIVED FROM SOIL WATER CONTENT DATA OF A LONG-TERM EXPERIMENT

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Introduction

Improving soil water management to maximize crop water supply requires a quantitative knowledge of soil hydrological properties. Principle among these is soil hydraulic conductivity (K), which is a function of soil volumetric water content (θ). $K(\theta)$ is defined by Darcy's law, which states that the flow of water q from one soil depth to another is proportional to the water pressure gradient between the two depths, $\delta\Psi/\delta z$:

$$q = K(\theta)\ \delta\Psi/\delta z \qquad [1].$$

Crop water supply is in many ways governed by $K(\theta)$, because it strongly influences rates of infiltration into, redistribution within, and drainage from the crop root zone. Crop water use, and therefore water-use efficiency, cannot be correctly calculated without a fairly accurate estimation of drainage from the root zone.

Field determination of $K(\theta)$ can be labour- and equipment-intensive, and therefore costly. Furthermore, point-determinations of hydrological properties in the field are difficult to extrapolate to nearby sites, because $K(\theta)$ has a semi-logarithmic spatial distribution. The ability to estimate $K(\theta)$ at the same location one is measuring soil water content permits a more accurate calculation of drainage from the root zone, and therefore of crop water use.

A field method for deriving $K(\theta)$ *in situ* from periodic soil water measurements was developed by Klaij and Vachaud (1992) to estimate root zone drainage in sandy soils of Africa. Payne (1997) used the method to estimate water use and water-use efficiency of pearl millet as affected by management, genotype, and climate. Klaij and Vachaud (1992) equated any increase in stored water within a soil volume, from one measurement date to the next, to water flow from above that volume (q of Eq. [1]), so long as water content at its lower boundary was small enough to assume negligible flow. The θ value at which flux occurred across the upper boundary of the soil volume was the mean of θ on the two dates of measurement. For the purposes of calculating root zone drainage, the upper boundary is assumed to be the depth of root zone (z_r), and the lower boundary is the lowest depth of soil water measurement. For several dates of measurement, then, one can obtain several corresponding values of q and θ.

Klaij and Vachaud (1992) and Payne (1997) made the assumption that the value of the hydraulic gradient of Eq. [1], $\delta\Psi/\delta z$, was unity. This assumption was valid for sandy soils, for which the curvature of the water content profile is generally small, so long as wetting fronts were avoided. The assumption reduced the calculation of $K(\theta)$ to a straightforward regression problem. The assumption of unity would not be valid, however, for soils with higher water retention capacity, such as the Walla Walla silt loam soil found near Pendleton. To be useful for crop water use studies in heavier soils such as these, an estimate of $\delta\Psi/\delta z$ is required.

The purpose of this study was to develop $K(\theta)$ functions from data on soil water content taken from a long-term winter wheat/pea rotation experiment at the

Pendleton research station. The results reported here are part of a larger study on the effect of climate and tillage on water use and water-use efficiency of the winter wheat/pea crop rotation.

Materials and Methods

The wheat/pea rotation study is one of several long-term studies located at the Columbia Basin Agricultural Research Center, near Pendleton, Oregon. What is fairly unique about this long term study is that neutron probe measurements were taken to measure soil water content from 1967 to 1989. The study used a randomized block design with four replications. Each replicate contained eight plots (two crops × four tillage treatments). The location of peas and wheat within a replicate alternated from year to year. Individual plot size was 24 × 120 ft. Each of the 32 plots had a neutron probe access tube installed to monitor soil moisture content to a depth of 6 to 8 ft, depending upon the depth of the soil profile.

Semi-dwarf soft white winter wheat was sown as soon after October 10 as soil moisture was sufficient for germination and early crop growth. The wheat varieties grown were Nugaines from 1967 to 1974, Hyslop from 1975 to 1978, and Stephens from 1979 to 1989. Peas were sown in late March or early April, and harvested in June or July. The fresh pea variety Dark Skin Perfection was used throughout this period. Wheat received 40-80 lb N/acre as ammonium nitrate (34-0-0) broadcast prior to seeding. Peas traditionally received 20 lb/acre as either ammonium sulfate (21-0-0-24S) or ammonium phosphate-sulfate (16-20-0-14S) broadcast every second pea crop. The east half of the experiment, where access tubes were installed, received 1800 lb. lime/acre in 1976.

From 1967 to 1989, neutron probe measurements were taken anywhere from three to several times during the crop growing cycle. Measurements were taken to a maximum depth of 8 ft at 1 ft intervals. To determine $K(\theta)$ at a depth of 4 ft (approximate rooting depth, z_r, of peas), only data were used when water storage between 4 and 8 ft increased from one measurement date to the next. This generally corresponded to periods between harvest of wheat, when the profiles were dry and flow past the deepest depth of measurement could be considered negligible, and the ensuing winter months, when soil profiles were being replenished by rainfall. Increases in water storage between 4 and 8 ft were divided by the number of days between probe measurements to express q as a daily rate. The average θ at a depth of 4 ft between those two dates was also calculated.

To obtain an estimate of $\delta\Psi/\delta z$, soil water retention data for the Walla Walla silt loam, from Pikul (1987), were scanned into a bitmap image. Point values for soil matric potential and water content were estimated from the bitmap image using the program WINDIG. A numerical curve was fitted to the scanned data points using Jandel's TableCurve. Corresponding values of soil matric potential were calculated for mean θ values of the layers above and below $\mathbf{z_r}$,. These θ values were determined from neutron probe data. $\delta\Psi/\delta z$ was then calculated by correcting for mean gravitational head of the two layers.

Eq. [1] was rearranged to solve for $K(\theta)$. These values were then log-transformed and regressed upon θ using the linear model

$$\log_{10} K(\theta) = \text{constant} + \theta \qquad [2].$$

A second multiple linear regression

model was evaluated using the model statement

$$\log_{10} K(\theta) = \text{constant} + \theta + \text{plot} + \text{plot}*\theta \quad [3]$$

where plot represents plot number (1–32), to test for heterogeneity between plots. The significance of the interaction term plot*θ can be used to test for heterogeneity of slopes. All statistical analyses were made with SYSTAT (vers. 7.0).

Results

The scanned soil retention curve data of Pikul (1987), and the fitted curve, are shown in Fig. 1. The equation

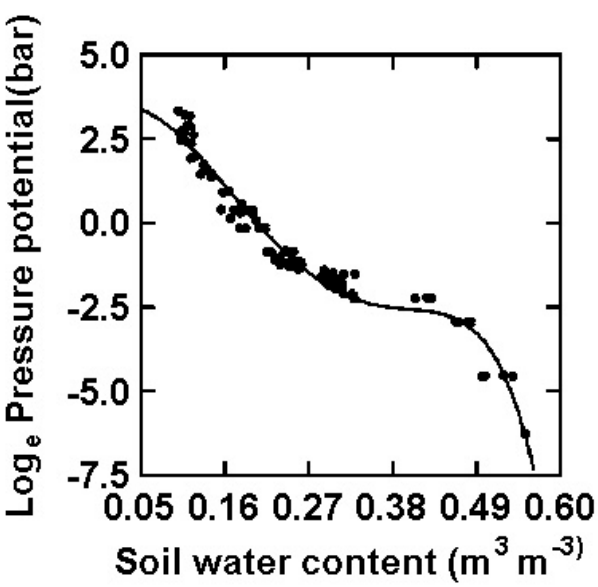

Figure 1. Soil water retention curve for Walla Walla silt loam at Pendleton experiment station. Data redrawn from Pikul (1987).

$$P = 3.043+56.582 + 612.6\theta^3 +154.5\theta/\log_e \theta$$

(R^2=0.96), where P is pressure potential (in bars), and θ is volumetric water content, related soil matric potential to soil water content with sufficient accuracy, as indicated by the R^2 value.

Among all neutron probe measurements taken during 23 years of data collection from the 32 plots, over 1300 met the condition that the amount of water stored between 4 and 8 ft increased from one measurement date to the next. This large number of points resulted in a very narrow 95% confidence interval for the regression model (Eq. [2]), despite the fair amount of scatter in the data (Fig. 2). These data suggest that, at a θ value of 0.30 m^3 m^{-3}, K=0.12 mm d^{-1}. For a hydraulic head gradient of unity, this would imply a root zone drainage of 12 mm in a 100 d period.

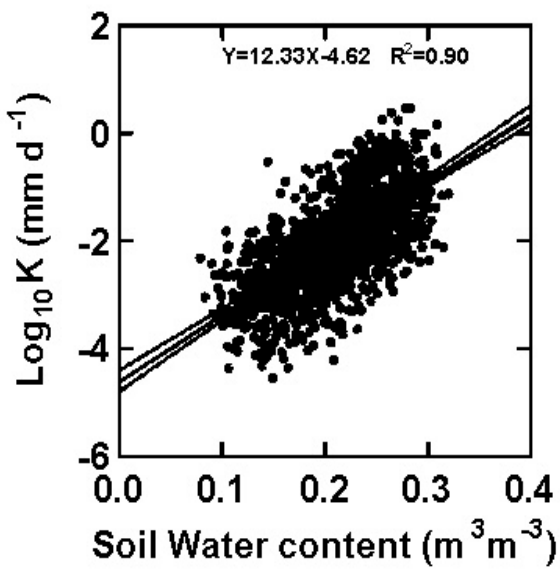

Figure 2. Hydraulic conductivity K(θ) as a function of soil water content at a depth of four feet for the Walla Walla silt loam at the Pendleton station. Data are pooled from thirty-two experimental plots.

The actual value of root zone drainage, however, would depend strongly upon the value of the gradient, as shown in Eq. [1].

Although the general linear model relating $\log_{10}$ K to θ provided a fairly good fit to the data, results of the multiple linear regression (Eq. [3]) revealed a highly significant interaction between θ and plot (data not shown). This indicates that the slope of the linear model was not the same for all plots.

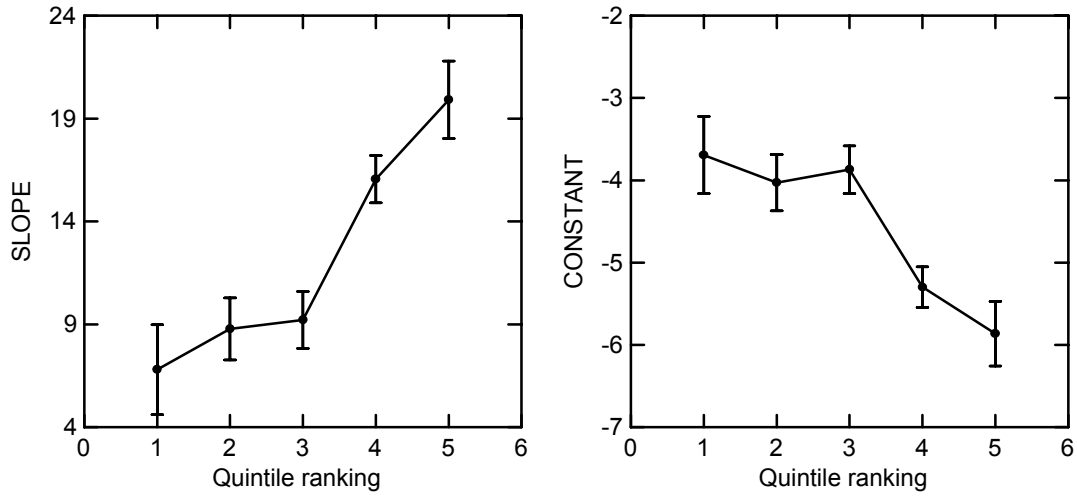

Figure 3. Slope and intercept of linear equations relating $\log_{10}$ K to θ for five groups of experimental plots. Bars represent one S.E.E.

Slopes of the lines fitted to data of individual plots were then ranked and divided into quintiles. The resultant slopes and intercepts, along with their standard errors, are shown in Fig. 3. The data show that slopes of the five quintiles are inversely related to intercepts. This effect is probably related to soil textural differences among the different experimental plots at a depth of four feet. Generally speaking, those plots associated with greater slopes and smaller intercepts would have slightly coarser soils, whereas those with lesser slopes and greater intercepts would have finer-textured soils.

Conclusions

The method of Klaij and Vachaud (1992) for calculating K(θ) and root zone drainage from existing neutron probe data has been modified to include an estimate of hydraulic head gradient. The method has been used to quantify soil hydrological properties for subsoil depths of the Walla Walla silt loam soil at the CBARC station with sufficiently high resolution to distinguish between spatially dependent hydraulic properties. This quantitative knowledge will help to better quantify crop water use, and therefore crop water-use efficiency.

References

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