Estimating Hydraulic Conductivity in the Vadose Zone Using GPR Techniques

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Introduction

Hydraulic conductivity is one of the most important parameters for understanding how water moves through the subsurface and is a critical component in environmental, agricultural, geotechnical, and geological applications. This research explores the potential of ground penetrating radar (GPR) techniques for estimating the hydraulic conductivity (K) of soil in the unsaturated zone at the field-scale. GPR data were acquired at a test site before and after irrigation, and these data were processed to determine the soil moisture distribution at each time. The unsaturated hydraulic conductivity (K_{unsat}) across the field was estimated from these moisture content values, and a map of the saturated hydraulic conductivity (K_{sat}) was produced using estimated van Genuchten's parameters and measured soil water content. To check the accuracy of these K_{sat} values, measurements of K_{sat} were acquired using a double-ring infiltrometer at selected locations within the field and were compared to K_{sat} estimates from GPR data.

Background

Conventional methods for measuring hydraulic conductivity are point measurements that are time-consuming and expensive to acquire. In contrast, GPR measurements are non-invasive, high resolution, and can be acquired quickly over large areas, and thus have great potential for characterizing the heterogeneous soils common to agriculture. GPR techniques cannot directly determine hydraulic conductivity, but instead can be used to measure the soil water content. By measuring the change in soil water content (Θ) over a known depth (z) before and after a wetting event, such as irrigation, the unsaturated hydraulic conductivity for a given water content (K(Θ)) can be determined:

$$\int_0^z \frac{\partial \theta}{\partial t}\, dz = \int_0^z -\frac{\partial}{\partial z}\left[K(\theta)\left(1+\frac{\partial \psi}{\partial z}\right)\right] dz \quad \text{Eqn. 1}$$

where t is time and is φ the soil suction.
If flow through the zone of interest is constant (no change in water content with depth), φ is also constant with depth, and the unsaturated flow equation is simplified to:

$$\left(\frac{d\theta}{dt}\right) z = \left(\frac{\theta_2-\theta_1}{t_2-t_1}\right) z = -K(\theta) \qquad \text{Eqn. 2}$$

GPR water content measurements acquired before infiltration (θ_1 at time t_1) and after infiltration (θ_2 at time t_2) can be used with Eqn. 2 to estimate K(θ_2). Unsaturated hydraulic conductivity is a function of water content, so to understand variations in hydraulic conductivity across a field independently of water content variations, the saturated hydraulic conductivity (K_{sat}) should be considered. To convert our measurements of K(θ_2) to K_{sat}, we assumed constant values for the effective porosity (n_e), residual water content (θ_r), and the retention curve fitting parameter (m), then used van Genuchten's method to estimate K_{sat} from the K(θ_2) and θ_2 values at each location. (Wosten and van Genuchten)

$$K_{sat} = K(\theta)\left(S_e^{0.5}\left[1-\left(1-S_e^{\frac{1}{m}}\right)^m\right]^2\right)^{-1} \quad \text{Eqn. 3}$$

Where

$$S_e = \frac{\theta-\theta_r}{n_e-\theta_r}$$

The study site was a gently sloping, 11-acre field site of predominantly coarse-grained soil in northern Wisconsin (Figure 1). Crops grown in the field alternate between corn and alfalfa, and the southeast corner of the field was irrigated using a pivot irrigation system (Figure 2).

Figure 1: The test site was at an agricultural research station in Spooner, Wisconsin. This research focused on the irrigated southeast corner of the field.

Figure 2: Pivot irrigation was used in the southeast corner of the field site. The crops that were grown during this research were alfalfa and corn.

Methods

GPR groundwave data were acquired in six rows before and after irrigation using a 500 MHz antenna to determine the water content (Figure 3) (Nickel et al). The sampling depth of the 500 MHz groundwave is approximately 20 cm; the water content distribution over this depth before and after irrigation is shown in Figure 4a and 4b.

Figure 3: GPR data were collected using 500 MHz antennas in six east-west traverses across the field.

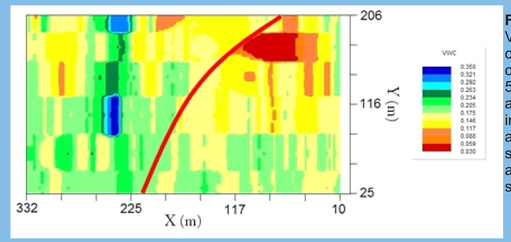

Figure 4a: Volumetric water content was calculated from the 500 MHz GPR data acquired before irrigation. The red areas indicate drier soils, while the blue areas indicate wetter soils.

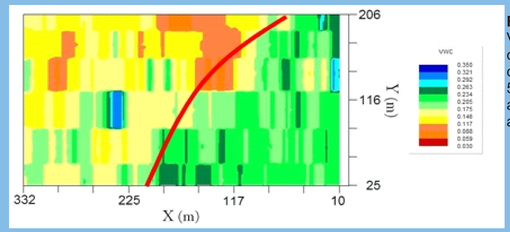

Figure 4b: Volumetric water content was calculated from the 500 MHz GPR data acquired immediately after irrigation.

The saturated hydraulic conductivity was estimated at each GPR sampling location using the method described in the Background section.To evaluate the accuracy of the K_{sat} estimates from GPR data, K_{sat} measurements were made using a double ring infiltrometer at 15 points across the field (Figure 5a and 5b). The locations for the infiltrometer measurements were chosen to cover a range of soil textures, based on previously acquired GPR data at this site.

Figure 5a: Conventional point-source measurements of hydraulic conductivity were acquired using a double ring infiltrometer. The first measurements were acquired in June 2014, when the corn crop was young.

Figure 5b: Data were acquired using the double ring infiltrometer in Oct. 2014, when the corn was mature.

Results

GPR data were used to estimate K_{sat} from the water content estimates acquired before and after irrigation (Figure 4a and 4b). Although the soil texture at this site is relatively more homogeneous than most agricultural sites (the soil at 14 sampled sites in the southeast corner ranges from 68% to 86% sand), K_{sat} varies significantly over the site; the high-resolution GPR data show that K_{sat} can change rapidly over only a few meters (Figure 6). The variation in K_{sat} is primarily caused by changes in soil texture (Figure 7.)

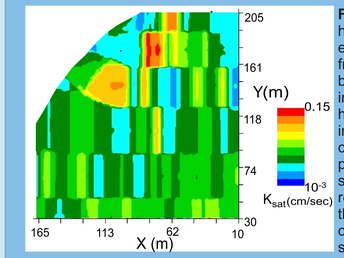

Figure 6: Saturated hydraulic conductivity estimates were calculated from the GPR data acquired before and after pivot irrigation. Areas with higher hydraulic conductivities are indicated by warm/red colors, while lower permeability areas are shown in blue. The high-resolution GPR data shows that hydraulic conductivity can vary significantly over short distances.

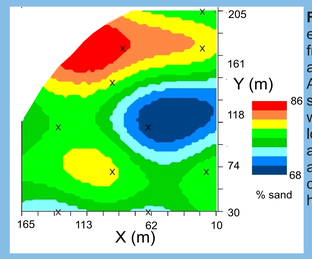

Figure 7: Percent sand estimates were calculated from the soil samples acquired across the field. Areas with high percent sand are indicated by warm/red colors, while lower percent sand areas are shown in blue. The areas of high percent sand correlate with the areas of high hydraulic conductivity.

To verify the accuracy of the GPR measurements, a double-ring infiltrometer was used to acquire K_{sat} measurements in the uppermost ~12 cm at 15 locations. Figure 8a shows the K_{sat} measurements from the double-ring infiltrometer. To better compare the K_{sat} estimates from the GPR and the infiltrometer, a map of K_{sat} was made using only the GPR measurements acquired at the same locations as the double-ring infiltrometer data (Figure 8b). The strong similarity between maps 8a and 8b indicates that GPR methods can accurately characterize the distribution of K_{sat} on the field scale.

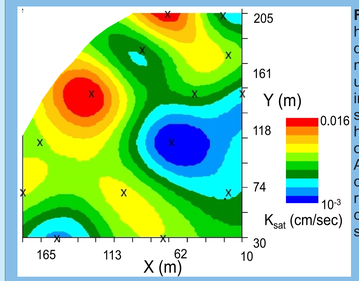

Figure 8a: The saturated hydraulic conductivity distribution for the 15 measurements acquired using the double ring infiltrometer shows significant variation in hydraulic conductivity over the study site. Areas with high hydraulic conductivity are shown in red, while low hydraulic conductivity areas are shown in blue.

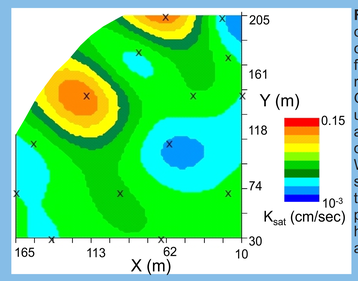

Figure 8b: To better compare hydraulic conductivity estimates from the GPR and double-ring infiltrometer data, the GPR data were sampled using only the 15 locations also sampled with the double ring infiltrometer. When similar numbers of samples are considered, the two techniques produce similar patterns of hydraulic conductivity across the site.

Conclusions

Using time-lapse GPR data before and after infiltration, estimates of K_{sat} in the vadose zone can be made. Estimates of K_{sat} from GPR data are similar in pattern to conventional double-ring infiltrometer measurements, but differ in magnitude, especially at high K_{sat} values. These differences may be caused by differences in sampling depths of the two techniques, imperfectly met assumptions about steady-state flow (which is necessary for the GPR-based methodology), or by the use of constant soil parameters to convert measurements of K(Θ) to K_{sat}. Future work includes sampling hydraulic conductivity at multiple depths using conventional methods for comparison with GPR data, considering alternative methods for K(Θ) to K_{sat} conversion, and performing numerical analysis and column infiltration experiments using different soil textures and soil moisture conditions to better understand the conditions of steady-state flow with regards to irrigation.

References

Nickel, C., T. Crist, S. Peterson, A. Benda, and K. Grote (2010), Three dimensional estimation of volumetric water content using multi-frequency GPR groundwave data, GSA North-Central/South-Central Joint Annual Meeting, Abstracts with Programs 42(2) Paper 44-8.

Wosten, J.H. and M. van Genuchten (1988), Using texture and other soil properties to predict the unsaturated soil hydraulic functions, *Soil Sci. Soc. Am. J.*, 52, 1762-1770.

Acknowledgments

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