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Determining Soil Hydraulic Conductivity from Cosmic-ray Neutron Data

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Introduction

Current methods used to quantify hydraulic conductivity require either lab testing of soil samples or the use of infiltrometers in the field. Obtained values are then used in climatological models to estimate soil moisture impact on the atmosphere, help with water usage in agricultural areas, and assist in predicting soil response (i.e. infiltration rates, time to ponding, and etc...) to storms. While these methods have been considered a standard in hydrogeologic studies, they often disturb the soil, can cause compression of the soil samples, and only provide a specific point measurement which is not representative of an area around the sample (Binley et al., 1989; Angulo-Jaramillo et al., 2000).

The recently developed cosmic-ray soil moisture method (Zreda et al., 2008), implemented in the COsmic-ray Soil Moisture Observing System (COSMOS; cosmos.hwr.arizona.edu), is a non-invasive way of measuring average soil moisture over a footprint that is a circular area with a diameter of 660m and over a thickness of decimeters. The method takes advantage of the strong inverse relationship between soil moisture and cosmic-ray neutron intensity in air above the soil surface (Desilets et al., 2010). By evaluating the summer and winter drying trends of the COSMOS soil moisture signal, it may be possible to estimate area averaged soil hydraulic conductivity values that account for large scale soil variability.

Methods

Study Site

The site used for this analysis is the Santa Rita Experimental Range (SRER) which has been on the COSMOS network since June 2010. Located at 31.9085N, -110.8394W, the COSMOS probe is approximately 40km south of The University of Arizona (Figs. 1, 2, and 3). The SRER probe location has a nearby eddy covariance flux tower operated by the School of Natural Resources and the Environment, a network of 190 time-domain transmission (TDT) sensors, and a COSMOS probe that was installed in 2010. The TDT sensors and 18 rain gages are divided amongst 18 stations located around the COSMOS probe at distances of 25, 75, and 175m and every 60 degrees from the COSMOS probe (Fig. 1). The SRER site is semiarid desert savanna that has been characterized as Agustin sandy loam with 5 – 15% gravel within the top 100 cm and no discernible caliche layer within that depth (Cavanaugh et al., 2011). The land cover at SRER is ~76% bare soil with creosote (Larrea tridentate) the dominant plant species at ~14% and the remaining ~10% accounted for by grasses, other forbs, and cacti (Cavanaugh et al., 2011).

Located in the American Southwest, the SRER study site experiences two distinct precipitation seasons; the summer monsoon season (May – October) characterized by highly localized, intense storms (> 20mm) and winter (November – April) with more frequent and expansive, but weaker storms (< 5mm). The SRER site has a calculated evapotranspiration (ET) rate of ~ 4 – 5 mm day\(^{-1}\) during the summer months and ~ 0 – 2 mm day\(^{-1}\) during winter (Scott et al., 2008).

Precipitation data was available from the TDT stations at the study site beginning in June 2011. However, flux tower data is not currently available beyond December 2011. To
accommodate for this, the water year beginning November 2010 and ending October 2011 was evaluated as it has complete flux tower data for use in estimating evapotranspiration (ET). The flux tower also has a single rain gage located nearby and it provided the precipitation input to the model for the period of November to July, when the TDT rain gage data was not yet available.

**Soil Moisture from Cosmic-ray Neutron Data**

The COSMOS probe (Model CRS-1000 from Hydroinnova LLC, Albuquerque, NM, USA) houses two $^3$He gas neutron counters. The plastic-shielded, gas neutron counter (Fig. 4) measures fast neutrons which are most sensitive to soil moisture changes. The fast neutron count is inversely related to soil moisture content (Figs. 5 and 6) (Desilets et al. 2010). Zreda et al., 2008 found that the sensor extent has a horizontal extent of approximately 335 m at sea level. With the elevation at the study site ~ 989 m above sea level, this horizontal extent is expanded to ~ 350 m because the decrease in neutron collisions with atmospheric gases is decreased with increased elevation from sea level.

**UMS HYPROP**

The UMS HYPROP (Sensor Unit from Decagon Devices, Pullman, WA, USA) uses the evaporation technique which is discussed in Peters and Durner, 2008. The UMS HYPROP uses two tensiometers to determine the pressure gradient within the soil samples and the change in sample mass from evaporation to determine the relationship of hydraulic conductivity to soil moisture (Schindler and Müller, 2006). For this device, seven samples were selected from the study site; the first sample was taken at the probe, three samples at a distance of 25 m were taken at 0, 120, and 240° from north, and the final three samples were taken at a distance of 75 m at 60, 180, and 300° from north. These locations were selected as they represent the bulk of the COSMOS sensitivity and were fairly representative of the variation in soil textures within the study site. Each sample was saturated from below over three days before being evaluated on the UMS HYPROP with the Decagon Device provided Data Evaluation Software. The fitted curves used the van Genuchten unconstrained and Mualem model to fit parameters to the drying trends of each saturated sample.

**Modeling the COMSOS Soil Moisture Measurements**

In order to evaluate the soil properties using COSMOS soil moisture data accurately, a model was created to empirically predict the drying of the footprint following precipitation events. The model used is empirically derived accounting for precipitation as the sole input to the system, and evapotranspiration (ET) or deep percolation (DP) as the only outputs. The equation below is the model that was used in estimating the COMSOS signal and relies on the Markov assumption of memoryless transitions between states.

$$\theta_i = \frac{1}{\sigma} \times \frac{P}{Z^* \times n} + \left(\theta_{i-1} \times e^{-\frac{1}{\beta} \times \frac{\Delta t}{24} \times (\theta_{i-1} - \theta_r)}\right)$$

In the above equation precipitation (P) is converted to an equivalent depth of water by the division of the probe measurement depth ($Z^*$) and the average porosity (n) of the footprint. Because the model assumes a Markov relationship, the current value of soil moisture ($\theta_i$) is dependent on the input (P), the previous soil moisture ($\theta_{i-1}$), and any fluxes out of the system.
(exponential decay). The exponential decay is controlled by the time step of evaluation ($\Delta t/24$) in hours per day, and the distance between the previous soil moisture value and the residual soil moisture of the soil type ($\theta_{i-1} - \theta_r$). Precipitation is regulated by the fitting parameter sigma ($\sigma$) which characterizes the percent of rainfall that is lost to overland flow and the spatial heterogeneity that exists in each storm over the COSMOS footprint. The other fitting parameter beta ($\beta$) is used as a proxy for ET and DP.

**Results and Analysis**

Fitting the model (Fig. 7) to the COSMOS signal revealed a number of interesting trends that are part of the ongoing investigation to the potential for determining the soil hydraulic conductivity from cosmic-ray neutron data. First, the dual season model used does provide a sufficient fit to most of the COSMOS data (Fig. 8). However there are significant errors at the beginning and ending of the winter season. These periods can, and in the American Southwest, often have temperatures 10 – 20°C higher than those found in the middle of the winter precipitation season. Because ET is very sensitive to temperature, this drastic change in atmospheric temperatures cause the model to underestimate the soil moisture during the beginning of the winter season and overestimate it by the end of the winter season. This is not seen as distinctly during the summer months because the temperatures are significantly higher, the precipitation is usually very intense and highly localized, and the time between storms is usually very short. This prevents an analysis of long drying trends which are possible during the winter months. This has prompted the creation of a new model which looks to classify the seasonality of the COSMOS signal into a three or four season model (winter, pre-monsoon, monsoon, and post-monsoon), or a monthly model that would calibrate based on the mean annual monthly temperature.

The UMS HYRPOR data revealed three possibly distinct groupings of soil moisture and hydraulic conductivity relationships (Fig. 9). These trends are being further evaluated through additional sampling of soils around the probe and extending out to 175 m from the probe, as well as an evaluation of the gravel wash located in the southern half of the COSMOS footprint as a high conductivity area. From this information it is hoped that a conductivity weighting may be able to be implemented that would best estimate DP flux within the footprint.

Flux tower data beginning in January 2012 is being requested from the School of Natural Resources and the Environment at the University of Arizona so that the 2011 – 2010 water year can also be evaluated using the same model parameters to check for repeatability as well as the predictive ability of the model to COSMOS neutron count derived soil moisture values.

**Continuing Work**

In order to determine if soil hydraulic conductivity values can be discerned from COSMOS soil moisture data a multi-season, and possible monthly, model is being designed to investigate the discrepancies in the current model. Once completed, and the current eddy covariance flux data is released, the ($\beta$) parameter may be more easily deconstructed into ET and DP fluxes. Additional samples from the study site are continuing to be collected and analyzed with the UMS HYPROP to better understand the spatial distribution of the differing soil types and the weighting factor of high conductivity areas, specifically the washes within the footprint.
Figures 1, 2, and 3. Santa Rita COSMOS probe location (from cosmos.hwr.arizona.edu and Franz et al., 2012). Figures depict the location of the probe, the sensitivity contours of the neutron counts, the location of the TDT network stations, and the landscape at the study site.
Figure 4. The interior of a COSMOS probe with the shielded $^3$He neutron counter outlined.

Figure 5. Relationship of soil moisture ($\theta$) and the neutron ratio ($\phi/\phi_0$). Fitting parameters ($a_0$, $a_1$, and $a_2$) are determined by calibrating the neutron ratio to volumetric water contents from soil sampling during probe installation (Desilets et al., 2010).

$$\theta = \frac{a_0}{\left(\frac{\phi}{\phi_0}\right) - a_1 - a_2}$$
Figure 6. Comparison of neutron counts with soil moisture from the San Pedro probe from 05/24/2011 to 09/30/2011.

Figure 7. Plot of the COSMOS measured soil moisture and the empirical model.
Figure 8. Comparison of the COSMOS measured soil moisture and the modeled soil moisture. Fit has an $R^2$ value of 0.9156 and SSE of 0.079 over both precipitation seasons. Largest area of discrepancy is at high SM values (peaks following precipitation events) indicates that the fitting parameter ($\sigma$) may be too large during the summer monsoon season specifically.

Figure 9. HYPROP generated soil moisture versus $\log_{10}$ hydraulic conductivity. Three distinct regimes seem to exist within this small sampling. Additional sampling around the probe is being conducted to augment these results and investigate zone of influence amongst the soil types.
References


