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Temporal dynamics of subsurface soil water content estimated from surface measurement using wavelet transform

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ABSTRACT

Temporal variation of water in the vadose zone is important to understand processes such as solute transport and nutrient cycling. Measurements of soil water content (SWC) in the subsurface are less common than those near the surface and predictions using numerical models are limited by data availability. Wavelet decomposition of surface measurements of SWC could improve modeling of subsurface SWC by segregating features at different temporal scales and projecting them to the subsurface. The objectives of this work were to: 1) predict subsurface SWC using surface SWC and a combination of wavelet analysis and linear regression, and 2) investigate relationships between soil properties and the movement of soil water at various temporal scales, *s*. Climate data and SWC at various depths were collected from eight sites in the Atlantic Coastal Plain of the USA. Soil water retention and hydraulic conductivity (*k*) functions of each horizon were optimized by comparing measured and predicted (using HYDRUS-1D) soil water contents. Each time series of SWC was decomposed into 50 scale components using the Mexican Hat wavelet and later reduced to 5 group components with minimal impact on the characteristics of the signal. Changes in the values of each group component with depth were represented with transfer coefficients that could be estimated with predictors derived from particle size distributions and optimized soil hydraulic functions. Prediction depth and saturated *k* were the two most important predictors for $s < 256$ h, while *k* at -10 kPa was the best predictor for $256\text{ h} < s < 724$ h, and the median value of particle size diameters for $s > 724$ h. Subsurface soil water content can be reasonably predicted with the proposed approach, particularly when vertical movement of soil water is unrestricted.

1. Introduction

Movement of water in the vadose zone is a complex process influenced by biotic and abiotic factors such as precipitation, composition of the soil profile (texture and structure of soil horizons), and evapotranspiration. A detailed characterization of the temporal dynamics of soil water content at various depths within soil profiles can help to better understand biochemical processes such as soil respiration, including the occurrence of sudden peaks of gas effluxes (hot moments) related to wetting and drying events (Borken and Matzner, 2009; Conant et al., 2004; Leon et al., 2014; Rubio and Detto, 2017; Wang et al., 2015). Detection of patterns of water distribution in soil profiles can also be used to identify subsurface flow pathways and to estimate leaching rate of solutes (Aparicio et al., 2008; de Rooij, 2000; Jarvis, 2007; Jaynes et al., 2001). Soil water storage is important for reducing uncertainty in weather forecasting and assessing extreme events (Koster and Suarez, 2001; Seneviratne et al., 2010), and soil water found at depths greater than 40 cm has been identified as an indicator of climate or weather extremes (Lakshmi et al., 2004; Tang and Piechota, 2009).

Recognition of the need of soil water content data with wide spatial coverage has prompted the development of new monitoring techniques (Ochsner et al., 2013) and the establishment of several sensor networks to measure soil water content, typically up to 1 m below the soil surface (Dorigo et al., 2011). The Soil Climate Analysis Network (SCAN) and the U.S. Climate Reference Network (USCRN) are the two largest of these databases with more than 200 sites throughout the USA, each with measurements at five standards depths (5, 10, 20, 50, and 100 cm) where sensor installation was possible (Dorigo et al., 2011). However, continuous records of subsurface soil water content are not available for many regions because instrumentation of soil profiles requires a significant monetary investment and is labor intensive (Dobriyal et al., 2012; Muñoz-Carpena et al., 2004).

Estimation of soil water content in the vadose zone over time and/or space is commonly done with numerical models (Vereecken et al., 2008). Most hydrological models require, at minimum, information on hydraulic properties of each horizon or layer forming a soil profile, and

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temporal information on rainfall and evapotranspiration (Simunek et al., 2005; Simunek et al., 2008; Vereecken et al., 2008). Soil hydraulic properties are difficult to measure, particularly when simulating non-equilibrium flow with complex models that require a large number of parameters (Allaire et al., 2009; Simunek et al., 2003). Estimation of soil hydraulic parameters with pedotransfer functions and available soil properties is a common practice (Vereecken et al., 2008; Van Looy et al., 2017), but it may introduce a great deal of uncertainty in model predictions (Finke et al., 1996). Alternative approaches to the estimation of soil water content include statistical models based on time stability of soil water content measurements. Typically, mean values are separated in space and/or time from their corresponding deviations, which can then be estimated with soil properties, vegetation, topography and climate variables (Hu and Si, 2016; Vanderlinden et al., 2012). In addition, analytical models have been used to produce long-term subsurface water storage from few soil parameters and meteorological data (Verrot and Destouni, 2016).

Measurements of soil water content near the surface are easier to make than deeper in the profile and can be used to reduce the uncertainty and improve prediction of subsurface soil water content (Das and Mohanty, 2006; Heathman et al., 2003; Kostov and Jackson, 1993; Kumar et al., 2009; Li and Islam, 1999). Techniques that incorporate surface observations into the estimation of subsurface soil water content include linear regression, numerical models, and the combination of remotely sensed data and water balance models (Kostov and Jackson, 1993). Linear regression is a simple approach to estimate soil water content at variable depths from surface water content, but can only be used when soil water movement at all soil layers is hydrologically connected and the temporal dynamics of soil water at the surface and at various depth are similar. However, processes such as precipitation, evapotranspiration, and soil water redistribution are likely to induce changes in soil water content at different rates. Thus, predictions with linear regression may be improved by treating periodic (seasonal) changes separately from relatively rapid and occasional changes of soil water content caused by wetting and drying events.

The wavelet transform is a technique that can extract periodic and non-periodic features from a signal by decomposing the original signal into a number of orthogonal components, each characterized by a given frequency (time or space) while keeping local information (Farge, 1992; Graps, 1995). Wavelet transforms have been used to investigate spatial variation of soil properties (Biswas and Si, 2011a; Lark and Webster, 1999; Lark and Webster, 2001), identify the controlling factors of soil water storage (Biswas and Si, 2011b), examine the temporal variation of soil water in relation to weather extremes, and to predict monthly temperature and seasonal precipitation (Lakshmi et al., 2004; Tang and Piechota, 2009).

Wavelet transforms may help overcome some of the limitations related to linear regression models because it is more suitable to evaluate the variation of a data series, such as soil water content, at different scales (Pachepsky and Hill, 2017). Wavelet coherence between two transformed data series is a measure of the linearity in their relationships in time (or space) at specific frequencies (Grinsted et al., 2004). Strong coherence between surface soil water content and rainfall time series are typically found at temporal scales ranging between 1 h and 2 weeks (Parent et al., 2006), which is likely a measure of the residence time of soil water in the surface horizons. The penetration depth of these short-scale features of soil water content signals is relatively shallow, and strong coherence between surface (5 cm) and subsurface soil water contents are consistently found at greater (256–512 days) time scales (Lauzon et al., 2004). Similarity in temporal patterns of soil water content between the surface and subsurface was also reported by Li et al. (2017). These results suggest the possibility of developing a wavelet-based statistical model for estimating soil water contents at the subsurface from the assimilation of surface soil water content at different scales.

The objectives of this research were to investigate 1) the potential for using wavelet transform (decomposition) of time series of near-surface water contents to predict subsurface water contents, and 2) relationships between soil physical properties and wavelet derived scale components, each representing changes in soil water content at specific time frequencies. The hypotheses driving this study are that: 1) several individual environmental processes influence soil water content at distinct time frequencies, with effects that are additive and altogether determine near surface soil water content at any given time, and 2) the temporal changes in surface water content can be transferred to the subsurface using linear functions with component-specific transfer coefficients. In this study, time series of soil water contents were decomposed into 50 scale components using wavelet transform, which were further clustered into 5 group components. Clustering was done to preserve signal information, while achieving a reasonable reduction in the dimension of the model with the aim of understanding soil properties controlling the transfer of water at various scales. Linear regression was used to obtain the transfer coefficients describing the relationships between the values of each component at the surface and at the depths of interest, while multivariable linear regression was used to explore correlations between those transfer coefficients and soil properties, such as water retention and saturated hydraulic conductivity (derived using a numerical model), particle size distribution, and depth to the observation point.

2. Materials and methods

2.1. Site characterization

Soil water content measurements, soil physical properties and meteorological data (hourly precipitation, air temperature, wind speed, relative humidity, atmospheric pressure, and net radiation) from eight sites located in the Atlantic Coastal Plain region of the United States

Table 1

Site index, name and location of 6 sites selected from the Soil Climate Analysis Network (S) and 2 sites selected from the New Jersey Weather and Climate Network (NJ) used in this study, and modeling periods used to simulate soil water content with a numerical model (HYDRUS-1D) and a wavelet approach.

Site index[a]	Site name	Location		Modeling period	
		State	Coordinates	HYDRUS-1D	Wavelet
S2049	Powder Mill	Maryland	39.02 N, 76.85 W	3/27–6/01/09	5/24/07–8/1/11
S2008	Tidewater #1	North Carolina	35.87 N, 76.65 W	3/03–5/26/09	8/21/07–5/31/13
S2013	Watkinsville #1	Georgia	33.88 N, 83.43 W	3/23–5/31/09	10/19/05–8/8/12
S2027	Little River	Georgia	31.5 N, 83.55 W	8/12–10/24/08	1/1/02–7/27/09
S2009	Wakulla #1	Florida	30.30 N, 84.42 W	2/16–5/22/12	7/14/98–4/15/03
S2012	Sellers Lake #1	Florida	29.10 N, 81.63 W	2/15–5/16/12	1/1/97–6/30/02
NJ295	Cream Ridge	New Jersey	40.12 N, 74.53 W	3/04–5/21/08	1/2/07–6/20/12
NJ284	Upper Deerfield	New Jersey	39.52 N, 75.20 W	5/06–8/03/08	1/2/07–6/20/12

[a] Except for leaf area index, all data for sites with index S were downloaded from the Soil Climate Analysis Network (NRCS, 2017). For the NJ sites, soil water content measurements and meteorological data were provided by Prof. David Robinson (New Jersey State Climatologist).