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On the relevance of using artificial neural networks for estimating soil moisture content

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Summary Soil moisture is a key variable that defines the land surface-atmosphere (boundary layer) interactions, by contributing directly to the surface energy balance and water balance. This paper investigates the utility of the widely adopted data-driven model, namely artificial neural networks (ANNs), for modeling the complex soil moisture dynamics. Datasets from three experimental soil covers (D1, D2, and D3), with thickness of 0.50 m, 0.35 m, and 1.0 m, comprising a thin layer of peat mineral mix over varying thickness of till, are considered in this study. Volumetric soil moisture contents at both the peat and the till layers were modeled as a function of precipitation, air temperature, net radiation, and ground temperature at different layers. Initial simulations illustrated that, in the absence of time-lagged meteorological variables, the ground temperature is the most influential state variable for characterizing the soil moisture, highlighting the strong link between the soil thermal properties and the corresponding moisture status. With the objective of extracting the maximum information from the most influential state variables (ground temperature), a higher-order neural networks (HONNs) model was developed to characterize the soil moisture dynamics. The HONNs resulted in relatively higher correlation coefficient, than traditional ANNs, for some of the soil moisture simulations. Time-lagged inputs were used to improve the model performance and obtain optimum results. The ANN models performed better than a previously developed conceptual model for estimating the depth-averaged soil moisture content. Results from the study indicate that modeling of soil moisture using ANNs is challenging but achievable, and its performance is largely influenced by the structure and formation of the soil covers, which in turn governs the dynamics of soil moisture variability.

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Introduction

Soil moisture content is a major control on several hydrological processes. Soil moisture determines the partitioning of available energy between latent and sensible heat (Entekhabi et al., 1996), and the magnitude of net radiation absorbed by the surface (Eltahir, 1998). Kuczera (1983) and Wooldridge (2003) have demonstrated that inclusion of soil moisture data in hydrological modeling can yield substantial reductions in the uncertainty of model parameters. Also, accounting for soil water content on catchement scales have proven beneficial for flow prediction (Kitanidis and Bras, 1980; Georgakakos and Smith, 1990; Wooldridge et al., 2003), and weather and climate studies (Georgakakos and Bae, 1994; Georgakakos et al., 1995). As these studies clearly highlight the role of soil moisture in hydrological modeling, the importance of understanding the dynamics of soil moisture cannot be over-emphasized.

Conventionally, field soil moisture estimates can be obtained by the gravimetric method or by the Time Domain Reflectometers (TDR). Although the field estimates of soil moisture are reasonably reliable, the problems (labor intensive, time consuming, expensive) associated with direct measurement of soil moisture, make these techniques quite impractical to characterize soil moisture patterns over an area. Also, heterogeneity in topography, soil properties, climate patterns, vegetation, and boundary conditions instill large amount of nonlinearity to the dynamics of soil moisture movement and distribution. Over the past decade, advancement in computer power and technology has made measurement of spatial distribution of soil moisture feasible using remote sensing techniques. However, soil moisture measured using these techniques may suffer from poor temporal resolution, and is representative of soil moisture content of the top few centimeters. Fully distributed, continuous water balance models have also been used to estimate soil moisture patterns (e.g. Wood et al., 1992; Grayson et al., 1995). The accuracy of soil moisture estimated by these models depends on the model physics and the number and configuration of soil layers, as well as the accuracy, and the temporal and spatial nature of the input data. As evident from the large number of publications, coupled modeling-remote sensing techniques (e.g. Grayson et al., 1995; Makkeasorn et al., 2006) is the most widely adopted procedure for characterizing soil moisture. Entekhabi et al. (1994) showed that the ability of such models to predict soil moisture averages over larger depths is severely limited by the noise introduced by micro-topography and roughness of vegetation cover. Since most of the methods have some limitations with regard to their ability in characterizing the soil moisture dynamics, there is clearly no single technique that can be adopted to estimate soil moisture in an operational mode (Entekhabi, 1996).

In light of the problems associated with the measurement and modeling of soil moisture using the above techniques, this study investigates the utility of the most widely adopted data-driven model, namely the artificial neural networks (ANNs), for estimating soil moisture. Although a plethora of studies have been carried out in the past to evaluate the efficacy of ANNs in hydrological modeling, for example, rainfall—runoff modeling (Hsu et al. 1995; Shamseldin 1997; Dawson and Wilby, 1998; Zhang and Govindaraju, 2000), streamflow forecasting (Karunanithi et al. 1994; Thirumalaiah et al. 1998), and rainfall forecasting (French et al. 1992; Zhang et al. 1997), the utility of ANNs in modeling soil moisture has rarely been reported in the literature. For modeling the rainfall—runoff relationship using ANNs, Dawson and Wilby (1998) used antecedent precipitation index based on earlier rainfall with the objective of approximating the soil moisture fluctuations. In modeling the runoff in a humid forest catchment using ANNs, Gautam et al. (2000) showed that soil moisture data obtained from 40 cm depth carry the integrated effect of the upstream catchment area, and are important for estimating stream discharge. These studies verify the importance of accounting for soil moisture in ANN modeling of hydrological processes. Since soil moisture has been shown to be an important variable in conceptual (e.g. Kitanidis and Bras, 1980; Georgakakos and Smith, 1990) and data-driven (e.g. Dawson and Wilby, 1998; Gautam et al. 2000) modeling of geophysical processes, the results from this study would be of interest to the hydrological community in gauging the utility of ANNs in characterizing the most complex and the most important hydrological variable, namely, soil moisture.

As neural networks belong to the category of data-driven models, proper input selection is a crucial step in any ANN implementation. The lack of pertinent inputs or the presence of redundant inputs in neural network modeling severely impairs the ability of the network to learn the target patterns. Several methods have been proposed in the literature to identify the effective inputs for neural network modeling, and a comprehensive treatise on this issue can be found in Bowden et al. (2005). The problem of identifying the effective inputs in neural network modeling is ill-posed if the pertinent variables for modeling a particular process are either not measured, or measured at different spatial and temporal scales. Hence, neural network modelers are often faced with the task of extracting the maximum information from the available (measured) independent variables. Kim and Valdés (2003), and Anctil and Tape (2004) used wavelet decomposed signals of the independent variables as inputs to neural network models, with the idea of providing the neural networks with information at different frequencies. Bowden et al. (2006) used principal components analysis (PCA) to reduce the dimensionality of the input dataset and to remove the collinearity present between the independent variables. Modular neural networks were also proposed with the aim of developing domain dependent input—output relationships (e.g. Zhang and Govindaraju, 2000; Parasuraman et al., 2006; Parasuraman and Elshorbagy, 2007). While the above discussed methods are promising, they are not straight-forward to implement. This study investigates the ability of higher-order neural networks (HONNs) (Gupta et al., 2003) to extract maximum information (judged by improved prediction accuracy) from the input data. The HONNs, in contrast to the widely adopted first-order neural networks (FONNs), has the ability to exploit self- and cross-correlation existing among inputs. The nonlinear and higher-order properties, if any, in the input space cannot be captured by the FONNs, as they employ only the linear correlation between the input vector and the