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Advancing Irrigation Strategies: Synergistic Modeling of Soil Moisture Using Cosmic-Ray Neutron Sensing, Hydrus-1D, and Machine Learning

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Innovative monitoring techniques today facilitate advanced and reliable measurements in the vadose zone. This, coupled with the predictive capabilities of machine learning, has an ever-growing impact on the management of agricultural and irrigation practices. The vadose zone, particularly the root zone, plays a pivotal role in hydrological processes by regulating water and energy fluxes across the soil surface. Additionally, it influences nutrient transport, groundwater recharge, groundwater pollution, microbial activity, and plant physiology, as it links the atmosphere, soil, and groundwater. Among various monitoring techniques, Cosmic-Ray Neutron Sensing (CRNS) stands out as a ground-based remote sensing technique capable of measuring soil moisture within the root zone at relevant scales (up to 240 m) with a high level of reliability. It is based on nuclear interactions between incoming cosmic rays and elements in the Earth's atmosphere, such as hydrogen. By employing the Hydrus-1D Cosmic module, effective soil moisture values can be derived based on the neutron intensity detected by Cosmic-Ray Neutron Probes (CRNPs). On the other hand, machine learning methods and neural networks (NN) hold enormous potential despite inherent limitations, notably the requirement for extensive datasets and their lack of a physical foundation in reproducing soil processes. In this study, we propose a synergistic approach to overcome these limitations. The physically-based Hydrus-1D model was utilized to train a single-layer NN for the direct prediction of soil moisture and irrigation water demand, relying exclusively on atmospheric forcings (temperature and precipitation) as input. In a proof-of-concept aimed at assessing the validity and robustness of our approach, a time series of synthetic data replicating soil characteristics, atmospheric forcings, and field measurements conducted through CRNPs was generated. These data were employed in the Hydrus-1D Cosmic module to calibrate a physically-based model, facilitating the generation of a continuous and extensive spatiotemporal soil moisture output dataset for the simulated synthetic field. The single-layer NN, trained with this synthetic soil moisture and atmospheric forcing data, demonstrated the potential to accurately predict soil moisture and irrigation needs of the terrain straightforwardly, using only atmospheric variables as input. The proposed synergistic approach has exhibited significant potential, and future developments in this research will involve the incorporation of real data.