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Penetration depth of Cosmic-ray neutron sensing for soil moisture under extreme vertical soil moisture gradients in measurements and modelling

Lena M. Scheiffele[1], Jannis Weimar[2], Daniel Rasche[3], Benjamin Fersch[4], and Sascha E. Oswald[1]
[1]Institute of Environmental Science and Geography, Subsurface Hydrology, University of Potsdam, Germany (lena.scheiffele@uni-potsdam.de)
[2]Physikalisches Institut, University of Heidelberg, Germany
[3]GFZ German Research Centre for Geosciences, Section Hydrology, Potsdam, Germany
[4]Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research (IMK-IFU), Garmisch-Partenkirchen, Germany

Cosmic-Ray Neutron Sensing (CRNS) delivers an integral value of soil moisture over a radial footprint of 150 to 240 m and a penetration depth of 15 to 83 cm. The support volume, especially in the vertical extent, decreases with increasing soil moisture. As the sensor is most sensitive to upper soil layers and the signal contribution decreases with increasing depth, the vertical distribution of moisture influences the signal received by the neutron detector. Additional soil moisture measurements are required to estimate the penetration depth of the CRNS measurement. These may be provided by profile measurements of a soil moisture monitoring network equipped with buried electromagnetic sensors. Different horizontal and vertical weighting schemes exist to compare the integrated CRNS value to an integrated (weighted) average value from a sensor network by adjusting reference measurements to the spatial sensitivity of the sensor. The vertical weighting was developed based on hydrodynamic modelling of a soil column and a neutron transport model (MCNPx). Since then the development of the Ultra Rapid Adaptable Neutron-Only Simulation (URANOS) opened up the possibilities for more complex neutron simulations to understand and interpret the CRNS signal. Simulations confirmed the large influence of soil moisture on the penetration depth of the sensor for homogeneous vertical soil moisture distributions, rarely occurring in natural environments. While in recent years the influence of horizontal heterogeneities on the signal generation was the focus of several studies, the influence of vertical gradients achieved less attention.

Against this background, we evaluate data from a field site in southern Germany with clayey soils and influence of shallow groundwater, where a CRNS is operated in parallel to a soil moisture monitoring network. We observe a good match between the time series of CRNS derived soil moisture and the weighted soil moisture from the sensor network during infiltration events. Several times during summer, however, topsoil dries and a strong vertical gradient develops (0.20 $m^3 m^{-3}$ in 5 cm to 0.50 $m^3 m^{-3}$ in 20 cm depth). During these periods the weighted sensor network underestimates CRNS derived soil moisture by up to 0.25 $m^3 m^{-3}$. We hypothesize, that the

estimation of the penetration depth does not hold for these extreme soil moisture gradients and that neutrons penetrate deeper into the soil and probe the wetter layers. The combination of observed neutron intensities as well as dedicated neutron transport simulations using the URANOS and MNCP6 model code will help to understand the site-specific signal behavior, explain differences observed in the data and lastly, gain information on the behavior of neutron intensities under vertically varying soil moisture contents.