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On the use of nuclear magnetic resonance for estimating the unsaturated hydraulic conductivity of soils on laboratory and field scale

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The method of nuclear magnetic resonance (NMR) is directly sensitive to the pore water and allows to estimate relevant information about the pore space (e.g., effective pore size) encoded in the relaxation behavior. Thus, it has great potential in hydrogeophysics and soil physics. NMR applications are available for investigations on laboratory and field scale, respectively. For saturated pore space empirical relations exist, that allow estimates of hydraulic conductivity from NMR relaxation data. Our research is focussed on the development of methods for estimating the unsaturated hydraulic conductivity K_U, which is the most important parameter when assessing water transport processes in the vadose zone.

Usually laboratory and borehole NMR relaxometry in relatively high magnetic fields (at least 1000 times higher than the earth's magnetic field) is used to estimate the pore size distribution (PSD) of the saturated material. For soil physical purposes the cumulative PSD related to the water retention function (WRF) is the key for predicting K_U when approximated adequately, e.g., with the widely used van-Genuchten-model (VG). We show with both artificial and real soil samples that the approximation of the NMR relaxation data with the VG model leads to plausible estimates of the VG-PSD index n only, if the clay content is smaller than approximately 10%. For higher clay contents the width of the PSD is underestimated by NMR in comparison with real WRF data as measured using a conventional pressure plate apparatus. This underestimation increases with increasing clay content because of the higher sensitivity of NMR to the pore bodies compared to the pore-throat sensitivity of conventional WRF measurements. Thus, we conclude that a plausible estimation of K_U from the cumulative NMR PSD is possible for sandy soils only.

When investigating various NMR measurements at different saturation degrees of the same material, we observed the occurrence of new relaxation regimes with decreasing saturation in both the T_1 and T_2 relaxation spectra. During desaturation the relaxation time spectra are shifted towards smaller times compared to the spectrum at saturation. This effect is caused by water that remains in the pore space during drainage as capillary-bound water in the pore menisci and as water films at the pore walls, respectively. This hypothesis is proved by numerical finite element modeling of the relaxation behavior of menisci water as well as by analytical desaturation models describing the relaxation behavior of water films in simple pore geometry.

With the help of the log mean of the T_2 relaxation spectrum at different saturation degrees we developed an empirical model based on the Brooks-Corey model that allows the prediction of K_U as a function of the saturation degree. This model is verified by column experiments in laboratory with sand of different grain sizes from fine to coarse.

Regarding the field application of NMR, i.e., the magnetic resonance sounding (MRS) method working in the earth's magnetic field, we had to modify our model for predicting K_U. This modification is necessary, because in MRS usually the so-called free induction decay is measured and the saturation dependency of the corresponding relaxation time T_2^* deviates significantly from the relations observed for T_2 measured by common laboratory NMR. Our approach of using T_2^* measured with earth's field NMR for estimating K_U is verified by column experiments in the laboratory. In principle this approach can also be used in MRS, if reliable T_2^* data from the vadose zone can be observed. We demonstrate this case with a field example. However, this interpretation scheme for MRS needs a priori information, which limits its general applicability yet.