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Reply on RC1

Mandy Kasner et al.

Author comment on "On soil bulk density and its influence to soil moisture estimation with cosmic-ray neutrons" by Mandy Kasner et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2022-123-AC1, 2022

Dear Reviewer 1,

thank you very much for your positive review. We will briefly respond to your concerns in the interactive discussion. (RC=reviewer comment, AR=author response)

 # Main comments

> RC1.0: "Overall, I think the authors did an acceptable job on simulation and lab experiment. However, the current version of the manuscript is not coherent or cohesive. There is plenty room for improvement in results presentation, content organization, and writing. Detailed suggestions and corrections are listed below."

AR: Thank you for your critical review and the suggestions to improve the manuscript. We will consider to restructure the text and to improve the writing throughout the revised manuscript.

##Specific comments

> RC1.1: "Relationship to lattice water and organic matter: I am curious about if any effects of lattice water that has already been considered in the lattice water correction are considered again in the bulk density correction. The case with organic matter is similar. As mentioned in Line 267-269, mineral soils without any organic parts were considered. However, the low bulk density of soil is usually the consequence of high content of organic matter. In practice, if I apply both the organic matter correction and bulk density correction to my neutron counts, do I over-correct it?"

AR: There is no risk of over-correction when correction for water-equivalent and bulk density are performed separately. As we have described in L43 and L269, lattice water and organic matter translate to an equivalent of water density, which is taken into account by the variable θ.

In general, epithermal neutrons are mainly sensitive to the density ratio between water and solid soil (as shown in section 2.1). They are rather insensitive to other properties of soils and molecular structure (see, e.g., Zreda et al. 2008, 2012 or Köhli et al. 2015). Hence, only those two components (soil density and hydrogen content) are to be considered when processing neutron data. In literature, soil density has not been

considered yet (other than converting from gravimetric to volumetric), which is the motivation for the present study. Soil's hydrogen content has to be corrected for the hydrogen in lattice water as well as in organic material, in order to end up with a quantity representing mobile water/soil moisture only (see line 43). In the state of the art, this is done by simply substracting lattice water and organic water equivalent from the total water content measured by CRNS. The reviewer is right that one should correct for these variables, but this will only correct for hydrogen-related effects and not for any bulk density effects. Hence, these corrections can be treated independently.

On the other hand, we fully agree that low bulk densities are often correlated with high organic matter content. The value pairs of high porosity and low (effective) water content are therefore not very common in typical landscapes. In L269 we have already indicated this concept (Soils with bd = 1 g/cm³ have low abundance and commonly include a high organic carbon content which introduces an additional effect to θ."). We will make more clear that the soil moisture values used in the equations and in the figures comprise the total hydrogen content, i.e., mobile soil water + lattice water + organic water equivalent.

> RC1.2: "Objectives and conclusions: The last two paragraphs of the introduction section need to be largely modified or rewritten. The hypothesis is only mentioned in this section but was not explained in detail how it is rejected/accepted and according to what criteria. To make the conclusion address the introduction, the objectives should be somewhat like 1) investigate the influence of bulk density in CRNS soil moisture measurement, 2) quantify the influence by examining the sensitivity of neutron counts through a large spectrum of soil bulk density, 3) assess the impact of bulk density on the two major conversion functions, and 4) develop a novel correction method/parameter for practical use."

AR: Thank you for suggesting a clearer structure for the outline of the manuscript, we will consider adapting the last paragraphs of the introduction section accordingly. The reason why we initially decided to start with the negative hypothesis -- that neutrons are invariant against change of soil bulk density -- was that this has been the hitherto common assumption in CRNS literature. However, we understand that a more straight-forward description of the hypotheses would be more clear.

> RC1.3: "Presentation of the results: The study provides substantial amount of simulation results. Many figures are clearly plotted and very informative. However, I feel a little awkward reading some of the figures. Based on the simulation and experiment design, I expected more figures like Fig. 5 with soil moisture as x-axis, and porosity contour lines, instead of the opposite, like Fig. 3. The presentation of Fig. 5 is similar to Fig. 6 in Zreda (2012) which is probably more common and easier to read in published literature."

AR: Thanks for sharing your impression regarding the presented figures. We agree that neutrons-over-moisture figures are more common in CRNS literature, which is why we decided to plot Fig. 5 this way to illustrate the effect for a typical application. But the main body of the study is the investigation of the measurement variable (neutrons) in responds to the changing variable (soil bulk density). As it is common sense to plot the independent variable on the x-axis, and the dependent variable on the y-axis, we believe that neutron-over-density plots most clearly show the dependency of neutrons on bulk density, while the additional dependency on water content is of secondary importance.

> RC1.4: "The lab experiment is of great value to this study, which could potentially provide a great validation dataset for the simulation. I wonder if there is any experiment on varying soil moisture conducted on this setup. It would be great if there were more points on Fig. 3 or a separate figure of Nexp vs. Nsimu. For Fig. 3 specifically, only 2 of the 4 experiment results were plotted in the figure. They were not colored with the soil

moisture color scheme, which can barely inform the readers with the performance of the simulation/experiment. I suggest plotting a zoom-in panel of the four points with four ideal contour lines of the soil moisture content equal to the four measurements. The four points should also be colored with same color scheme.

AR: Thank you for the suggestions. We will improve this figure visually and we will consider adding more data points if applicable.

> RC1.5: "Notation: The notations in this paper are generally clear but some selections are not very common. For dry bulk density, I think ρb is more common and ρs is often used as the density of solids instead of bulk density, which may cause some confusion. For Section 3.1, "soil-water ratio" may be better named as "solid-water ratio". You may assign this ratio with a symbol since it is also used in Table 1 and Section 3.3."

AR: Thanks for the suggestions. From the physics point of view (section 2.1), dry soil bulk density is equivalent to the solid part of the soil, so we used abbreviations s (solid), w (water), and a (air) for the three main components, and we tried to be consistent with this notation in the remaining manuscript. Using ρb for soil bulk density would require a redefinition of ρs = ρb, which would be unnecessary and redundant. But we understand that it would be helpful to use the notations more common in soil science. Hence, we will reconsider the notation of dry soil bulk density in the revised manuscript.

> RC1.6: "The correction factors: Some of the correction factors depend on soil moisture, which doesn't really "go in line with the traditional correction factors for atmospheric changes…" (as mentioned in Line 337), since I think the correction factors should be independent of soil moisture. Line 374-375 mentioned a TDR sensor. Does it mean that a point-scale measurement or some rough estimate can also work here?"

AR: We fully agree that the moisture-dependent correction is unconventional and may lead to a circular problem. The approach for correcting the road effect showed similar characteristics (Schrön et al. 2018). We tried very hard to find a solution that is independent of soil moisture, but unfortunately we cannot "work against the rules of nature". While moisture-dependent correction leads to the best performances, the good news is that moisture-free approaches also showed acceptable performance -- if the rough moisture regime is known (see the first two rows in Tables 2 and A1). So, yes, a very rough estimation of soil moisture is sufficient to achieve a decent correction performance. We will stress out this aspect more clearly in the revision.

 # Technical corrections

AR: Thank you very much for your time to hint at technical issues and for making adequate suggestions. We will consider them thoroughly in the revised manuscript.