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Reply on RC1

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Author comment on "Technical note: A revised incoming neutron intensity correction factor for soil moisture monitoring using cosmic-ray neutron sensors" by Magdalena Szczykulska et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2021-564-AC2, 2022

We thank the reviewer for the comments. Below are our responses.

- *"The Authors present a revised incoming correction factor that could be used for improving soil moisture estimated with cosmic-ray neutron sensing (CRNS). The topic is interesting and timing and probably the study fits a technical manuscript in HESSD. The analysis is based on the extensive datasets collected within the COSMOS-UK sites and the manuscript is generally also well structured and written."*

We thank the reviewer for appreciation of our work and for the positive general comment.

- *"[1] the study proposes a revised factor (eq.8) and the results are compared to the state-of-the-art (eq. 3). However, as far as I have understood, it is also well known an additional method (eq. 4) that so far it seems to be not widely adopted by the "CRNS community" but only used in some studies e.g., (Howat et al., 2018). So why do the Authors did not test this "not so common" revised method before proposing something new?"*

These approaches were tested, but we did not report this in the paper. We will add a comparison of the different correction approaches and how they affect the corrected counts and volumetric water content (VWC) at the COSMOS-UK sites. In particular, we will provide a comparison between our approach and the approaches given in Hawdon et al., 2014 (i.e. gamma based on cut-off rigidity approach and a nearest neutron monitor based approach).

To add for clarity, Howat et al., 2018 give gamma for a particular site in Greenland using a neutron monitor (THUL) also located in Greenland, so their result is for that particular case study.

- *"[2] as far as I have understood, the revised factor (eq.8) converges to what was currently available but not widely implemented (eq.4) not only in the form but, even more important, to the actual parameter i.e., G = 1.2 vs. gamma = 1.19 (See (Howat et al., 2018)). So, did I misunderstand or should the Authors be already satisfied by using eq. 4 without the need to propose a revised factor?"*

Howat et al., 2018 obtain the value of *gamma* = 1.19 (or *beta* as stated in the paper) for a particular site in Greenland without explanation beyond 'based on regressions to the global neutron monitor dataset'. Our study details how to derive *G* values at specific COSMOS-UK sites (there are 48 of them), so site specific incoming neutron intensity corrections. These site specific *G* values vary between 1 and 1.5 for the COSMOS-UK network. While the mean value across sites seem to converge to 1.2, it is not the case at individual sites.

We will clarify this aspect in the manuscript.

- "*for the development of the new revised factor (eq.8) the Authors compare incoming neutrons from RNMS (e.g., Jungfraujoch) to CRNS neutrons locally collected at a soil moisture site (SMS) during period where it is expected low variability due to soil moisture changes. Namely, removing local influences due to soil moisture, variability in the neutron counts should then be related to incoming fluctuations. The Authors then compare these local fluctuations to the RNMS. It is well discussed that, if these fluctuations are not the same, on a longer term, should be due to different cutoff rigidity and altitude between the RNMS and SMS. But since also eq.4 was developed to account for these factors, from my understanding it should be not a surprise that this revised method converge to eq. 4. So, overall, it seems to me that the Authors simply analyzed some time series and found empirically what is already know and addressed in literature. I might be wrong but, if this is the case, I encourage the Authors to clarify and improve the manuscript to better convey the novelty of the study.*"

The local fluctuations at SMS are different from RNMS due to the differences in cut-off rigidity and altitude, but also likely due to other differences, such as detector differences and site conditions. Whilst the CRNS detectors each have nominally the same response function as each other (but different to the RNMS), it is the interplay between the CRNS response function and the local SMS neutron environment (neutron energy spectrum) which can lead to site specific values of *G* (or *gamma*), even for sites at the same cut-off rigidity. For example Weimar et al., 2020 note that "The relative thermal contribution of the signal of the standard CRNP is in particular large for moist soil." It is also worth noting that none of the detectors deployed for COSMOS-UK have any thermal shield, so will be susceptible to thermal neutron leakage. In the revised manuscript, we will properly discuss these and other effects (e.g. wet soil generated neutrons) which may affect *G*, and in turn suggest possible physical interpretations of *G*.

Eqn. 4 accounts for some of the differences between SMS and RNMS by normalising neutron intensities at time of interest to a reference value (I/I_{ref}), but also via gamma. Hawdon et al., 2014 relate gamma to cut-off rigidities of locations of interest. This does not take into consideration the other above mentioned differences which do not necessarily cancel out via I/I_{ref}. In Howat et al 2018, both the cosmic ray neutron sensor and the reference neutron monitor are located in Greenland. The authors are primarily concerned with elevation differences and find *gamma* = 1.19 for that specific case study.

COSMOS-UK sites and the Jungfraujoch neutron monitor have very different location characteristics when compared to the study conducted by Howat et al., 2018. We also do not try to say that *G* has a single value for the whole COSMOS-UK network, but rather we investigate each individual site and find that *G* varies between 1 and 1.5, and we only report in L 144 that the average value of *G* is 1.2. We will clarify this point.

The novelty is that we calculate *G* for each individual COSMOS-UK site using directly neutron count data from the local site of interest (so we do not have to make assumptions about what causes the differences). We take a data-centric approach, and find the relationship directly from the data. While these neutrons are subject to soil moisture variability, we use a lower quartile regression fitting to put more weight on the wetter points (lower count rates) which have more constant soil moisture in the case of the UK. This method successfully reduces the unphysical drying trend in the CRNS soil moisture observations at wetter COSMOS-UK sites, for instance Glensaugh, when *G*=1 and provides better performance in this case when compared to *G* based on cut-off rigidity as given by Hawdon et al., 2014. This is an indicator of other influences which, as above, we will discuss further in our revised manuscript.

We will improve the manuscript to stress where the novelty of this study lies.

- "*[4] my last comment is related to the general assumption that incoming neutron counts from a RNMS adequately represents the relevant incoming neutron flux at the SMS and the revised factor accounts for some additional differences (L61-63). Based on that, the Authors conclude and suggest (L165-171) several research activities that could be performed for further improvements. Indeed I agree that using incoming fluctuation from RNMS is a first order correction that has to be considered also for CRNS applications. This assumption has however two shortcomings that should be considered. First, time series at RNMS need also several corrections that are still under investigations and the focus of current research activities and improvements. Thus, these time series are not error-free. Second, some local incoming fluctuations at SMS are not detected by RNMS. Thus, these time series could not well inform local incoming fluctuations even in the case they were error-free. For these reasons, personally I do not see a good suggestion to push much effort in improving a method that is based on input (i.e., the time series at RNMS) that has these drawbacks. In contrast, I have seen that the use of alternative detectors installed directly at the SMS for the detection of incoming fluctuations has been suggested in literature using e.g., muons detectors (Stevanato et al., 2019; Stowell et al., 2021) or neutron spectrometers (Cirillo et al., 2021; Fersch et al., 2020). Personally, I believe that improving and working with these approaches could be much more valuable suggestions for further studies and developments instead of improving the manipulation of no error-free and non-representative time series from RNMS. Alternative, a discussion of the added value of the present revised factor in comparison to abovementioned approaches should be reported.*"

We thank the reviewer for this helpful comment – yes we agree that (as above) there will be neutron energies (epithermal and thermal) which the CRNS detects, but not the RNMS. Indeed, for future work, the promising development of local reference detectors should be considered as a significant advancement, where affordable. We will add a brief discussion of these approaches.

However, given that for COSMOS-UK alone, we now have more than 5 years of data for 48 sites, with no in situ reference measurements, it is of great value to improve the long-term bias correction of the derived soil water content of these historical datasets, using the RNMS approach. Furthermore, our analysis of *G* across the whole of the COSMOS-UK network is valuable to highlight what improvements may be required (such as the deployment of reference detectors), and their relative cost-benefit.