Author Response to Reviewer #1 from

Improving Calibration and Validation of Cosmic-Ray Neutron Sensors in the Light of Spatial Sensitivity – Theory and Evidence

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RC: ***Reviewer Comment***, AR: *Author Response*, ☐ Manuscript text

Dear Anonymuous Reviewer #1,

we are greatful for the positive review and the helpful comments and suggestions. Please find below our response to the main points. Every single specific comment will be addressed in the revision.

1. Reviewer #1

1.1. Major concern #1

RC: ***The author claimed that the revised weighting approach has the potential to reveal otherwise invisible hydrological features, like water ponding in remote or local areas, water in the biomass or litter layer, interception water storage, groundwater rise etc. On the other hand, such claim is based on a simplified interpretation by using a lump-sum expression of "excess water storage" in Figure 8. This renders the statement on a weak ground. Unless there are other experimental results or numerical simulation results can provide further proofs for this statement, I am not convinced with this statement by only looking at Figure 8.***

AR: *Thank you for pointing this out. The CRNS indeed is an integral signal which is only able to sense "excess water storages" when combined with independent soil moisture measurements. From the dynamics of that signal (e.g., following rain events) and additional supporting observations, it is then possible to infer hydrological processes, such as interception or ponding. In the case of* Großes Bruch *ponding was actually observed during these days (see Fig. 1 in this very document). In the case of* Wüstebach*, Bogena et al. (2013) quantified water in the litter layer and observed ponding all over the catchment. To further support these interpretations, Figs. 7 and 8 included information about ground water rise in the same periods.*

While the mentioned additional information gave us evidence about additional hydrogen pools, we agree that the CRNS cannot distinguish between different pools. In the revision we will change that statement accordingly throughout the manuscript, using the term "excess water storages" as was suggested by you.

RC: ***Furthermore, the area difference between the "CRNS fit" and "revised" curve has two parts: one part is above the "revised" curve, and was defined as "excess water storage"; the other part is below the "revised" curve. However, for this "below part" there is no any explanation.***

AR: *This is a good question. As can be seen in the plot, the light blue curve goes below the blue curve many times throughout the period, and the maximum deviation always has a similar value ($\Delta\theta_v \approx 5\,\%$). We think that in these (dry) periods the CRNS signal mainly reflects the actual soil moisture, while in the other periods excess water storages are present. Thus, if the CRNS would be calibrated only on the dry periods, the lines*

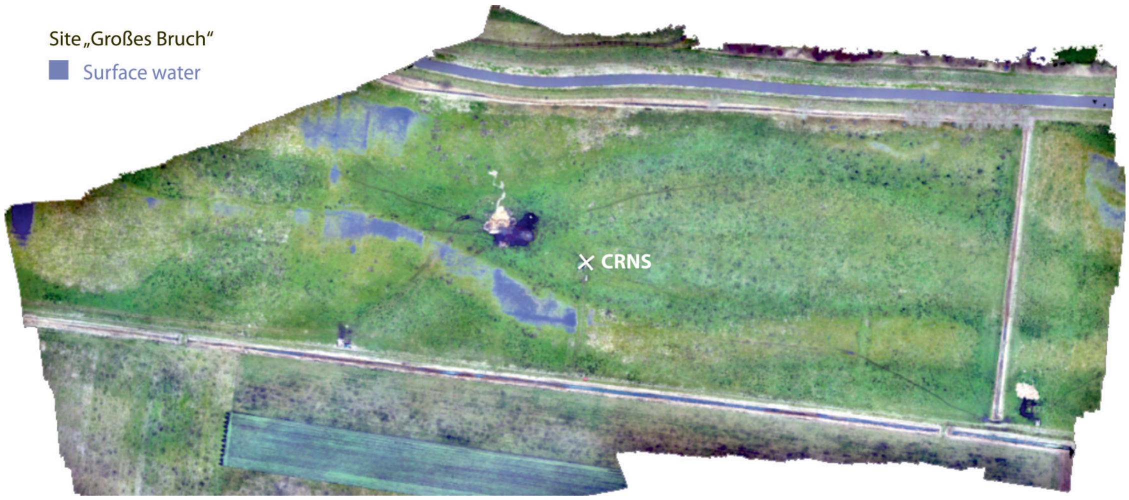

Figure 1: (not in the paper) UAV-derived orthophoto showing ponded water at the site *Großes Bruch*.

would match very well, and most deviations would be positive (towards the wetter state), reflecting excess water storages. However, for the sake of comparability, we show only the calibration on the full period, as was done also for other sites. It is remarkable that even in this case better performance plus identification of excess water storages has been achieved using the revised approach. When the dataset would be used in future studies to identify those hydrological features, we would recommend to recalibrate the sensor only on the dry days. In the revision, we will add this discussion to the text.

1.2. Major concern #2

RC: ***It is very confusing when the authors mentioned "theoretical line" "conventional" "revised", "equal". To my understanding, the "theoretical line" refers to the Equation (1), and the N0 is determined by using the standard sampling scheme as defined by Hydroinnova-soil (e.g. Desilets et al. 2010). For the standard sampling scheme, the equal weighting is deployed for horizontal and vertical samples. Then, how to distinguish this "theoretical line" with "equal" approach? Please help to make all implications for different approaches more explicitly.***

AR: *The procedure we followed is actually less complicated. The theoretical line – the relation between neutrons and water equivalent – is independent of the weighting strategy. Desilets et al. (2010) determined it using neutron physics simulations and exprimental data at mostly homogeneous sites. Thus, this relation can be considered as a fundamental relationship of the CRNS method. We found that it can be confirmed at best by observations if the revised weighting approach is used. We suggest to add a schematic and flow chart of the procedure to make clear that the* N_0 *parameter of the theoretical relation can be calibrated using average soil moisture obtained by either the equal, conventional, or revised approach (see Fig. 2 in this very document).*

RC: ***It is also recommended to list all different methods into a summary table, which will help readers to understand the topic easier than the currently presented.***

AR: *Thank you for this suggestion. In this work we applied three methods: equal weighting, conventional weighting, and revised weighting. These are explained linearly in the methods section. We think that a summary of these methods in a table is redundant and would not add substantial insights about the procedure.*

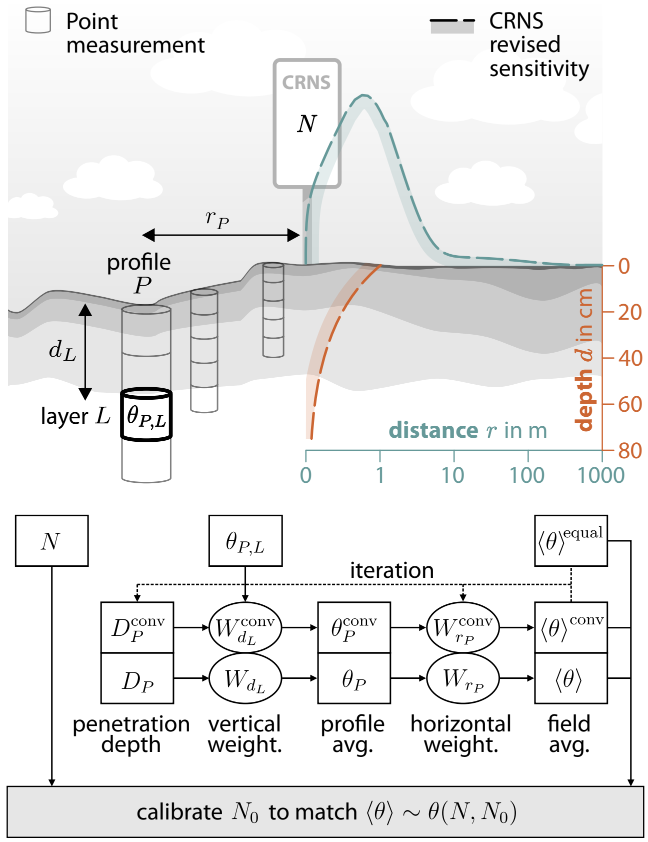

Figure 2: (will be added to the paper as new Fig. 3) Top: Schematic of the environment around the Cosmic-Ray Neutron Sensor (CRNS) including point measurements (e.g., soil samples) of water equivalent θ to calibrate or validate the sensor. The revised sensitivity functions W_r (teal) and W_d (brown) are indicated, the omitted y or x axes express their sensitivity at arbitrary scale, respectively. Bottom: The measured variables are used in the weighting procedure (section 2.3), starting with an initial estimate of field-average water content. Three approaches, using the *equal*, the *conventional* (conv), and the *revised* weighting function are compared in this study. The resulting weighted-average water equivalent $\langle\theta\rangle$ is then used to calibrate against or validate with the CRNS product (eq. 1). Calibration of the parameter N_0 is performed towards optimization of four performance measures (see section 2.5).

Instead, we will follow your advice to illustrate more clearly what the methods are and how the weighting procedure works. Therefore we will add a single-column figure, including a schmetic of the CRNS footprint, the point samples, and a flow chart of the weighting procedure (see Fig. 2 in this very document).

1.3. P3 L27 eq. 1

RC: ***what is N should be explained as well.***

AR: *N denotes the corrected neutron count rate as explained in the sentence before:*

> To convert the neutron count rate N to gravimetric soil water equivalent, θ, Desilets et al. (2010) suggested the following theoretical relation:
>
> $$\theta(N) = \frac{0.0808}{N/N_0 - 0.372} - 0.115\,, \quad \text{(Desilets et al. 2010)}$$

1.4. Fig. 1 annotations

RC: ***move title to y axis***

AR: *We like to keep the y-axis label on top of the plot to improve readability (non-rotated text, and larger figure size due to a smaller left margin). We think it is further obvious that the label at the top refers to the y-axis, since a plot by definition shows $y = f(x)$, such that the title of a plot is equivalent with the title of y.*

RC: ***please delete 'revised' here, while use 'rev' as superscript.***

AR: *We do like to keep written text in plot legends as the figure is then easier accessible by readers, compared to only showing a symbol. We further like to keep the convention of using symbols W, D, $\langle\theta\rangle$ for the revised approach, and W^{conv}, D^{conv}, $\langle\theta\rangle^{conv}$ for the conventional approach. Putting ^{rev} on top of the symbols would further complicate the presentation in this mansucript. The revised approach is the main protagonist in this work, and references to these symbols occur many times all over the paper, partly adding further symbol annotations (e.g., W_r^*).*

RC: ***how this ["equal, 1"] is determined? not described in the context, not in the caption as well.***

AR: *Thank you, we will add a description to the caption that we normalized the weights of 12 sample points (then, the equal weights give 1/12 for each point). Nevertheless, this is an exemplary and arbitrary value.*

RC: ***use cm^3 cm^-3 as unit. Please check it throughout the whole manuscript.***

AR: *We do not see urgent needs to use cm^3 cm^{-3}, mm^3 mm^{-3}, or any other equivalent unit. We think volumetric percent (%) is a much simpler unit and integer numbers are easier accessible for readers than decimal fractions. However, in the revision we will follow ISO80000 standards, by removing the indices from units like $\%_{vol}$, and instead will add indices to the variables, e.g. $\theta_v = 3\,\%$. We will also change axes labels for soil moisture in all figures to "Vol. soil moisture θ_v in %". To clarify the convention, we will also add a short note to the methods section.*

RC: ***Please use a common symbol to denote penetration depth***

AR: *Thank you, we will change to symbol D for penetration depth all over the manuscript. The fact that we still mention z^* and D_{86} has historical reasons, since these symbols are already well known to denote penetration* *depth in previous literature.*

1.5. P5 eq. 2

RC: ***what is denoted by 'd'? geometry depth? Please put it in the text.***

AR: *The variable d denotes the vertical depth of soil moisture measurements as explained in the paragraph before:*

> Therefore, independent soil moisture measurements taken at different depths, d, need to be weighted differently in order to account for the underlying physical processes. To show the consequences of neglecting this step in post-processing, we have compared the *equal* average of soil samples with alternative weighting approaches. The *conventional* vertical weighting, W_d^{conv}, is performed using a linear relation from Franz et al. (2012b), which was based on Monte-Carlo simulations from Zreda et al. (2008) and became widely accepted in most previous studies.

1.6. P7 L5 "while estimations of soil bulk density exist for every profile (or even every sample)."

RC: ***Does not 'profile' include 'every sample'?***

AR: *In general, a soil profile could have multiple samples (in different depths). Thus, bulk density information could be available for each profile (i.e., a vertical average), or even for each sample in the profile (i.e., a vertical distribution of bulk density information).*

1.7. P7 L8 "The procedure to obtain a weighted average of soil water equivalent is described as follows"

RC: ***Please use a flowchart to assist your description here. Please also include equation numbers in the flowchart.***

AR: *Thank you for this suggestion. We would like to include a flow chart as a new Fig. 3 in the paper, which is Fig. 2 in this very document. We did not include equation numbers, because all relevant equations are bundled in sections 2.2–2.3.*

1.8. P8 L5

RC: ***what is the converge criterion?*** $|\theta_t - \theta_{t-1}| < 0.0001$ ***?***

AR: *The criterion depends on the accuracy level that is relevant for the individual study. Typical uncertainties for CRNS products are at about* 0.02 *volumetric percent. The convergence criterion could be half of that. However, we would not like to prescribe this value. We will clarify this in the text.*

1.9. P10 L3

RC: ***is this N0 calibrated by using the weighting procedure as described in 2.3***

AR: *Yes, we will clarify and illustrate this in a new Figure (Fig. 2 in this very document, see above).*

1.10. Section 3

RC: ***It is recommended to provide the dominant basic soil texture information, bulk density, porosity, soil organic content for all sites considered here. At least for the <10m footprint of CRNS.***

AR: *Thank you, we will move parts from Table 1 into a new table, which will be dedicated only for study site descriptions. Therein we will add information about bulk density and other hydrogen pools as suggested.*

1.11. P12 L24-25

RC: ***Please help indicating which site is used for calibration, which site is used for validation.***

AR: *We calibrate the CRNS at every single site. The weighting approach is necessary for both, calibration and validation of the neutron sensor. However, in this work we only calibrate the sensor on the given sampling campaigns data or time series data. In the revision, we will avoid the word "validation" in the context of time series data throughout the text to clarify this. Further clarification will be also given in the new Table 1 and the new Fig 3 (Fig 2 in this very document). Clarification will be also added to the text.*

1.12. Fig 4 caption

RC: ***How this line (or N0) is determined? By following the standard sampling procedure as recommended by Hyroinnova-Soil?***

AR: *The theoretical line (including N_0) is determined by calibrating the CRNS on the weighted-average of point measurements as described in the methods section. We will add a schematic and a flow chart (Fig 2 in this very document) to clarify this.*

1.13. P13 L9, "reveal a single site-specific calibration curve"

RC: ***what are you referring to here? Do you mean unique?***

AR: *Yes, the parameter N_0 can be calibrated with a single calibration day dataset. This would lead to a single curve, $\theta(N, N_0)$. The three calibration days presented here lead to three distinct curves when the* conventional *weighting approach is used. However, since N_0 is assumed to be a site-specific, static parameter, we would expect all calibration datasets to agree with each other. The* revised *approach brings those three datasets in line, such that a unique parameter N_0 (and thus a single curve) can explain all three sampling campaign datasets. We agree to the reviewer that "unique" would be a better choice here and will change that as suggested.*

1.14. P13 L10-12

RC: ***Please provide quantitative description on the horizontal weights used.***

AR: *We do not understand what the reviewer means with "quantitative description". The horizontal weights W_r are calculated using equations in the methods section, and illustrated in Fig. 2. We will add a new flow chart (Fig. 2 in this very document) to illustrate how the horizontal weights are applied to a dataset of points.*

1.15. Fig. 5 caption

RC: ***It is very confusing which line indicating which data set.***

AR: *We tried to make the connection clear by letting the lines pass through their corresponding ellipses. For further understanding, we will add clarifications to the caption.*

1.16. Figure 6, “CRNS fit to revised”

RC: ***did you mean N0=1172 here?***

AR: *Correct. Each parameter* N_0 *resulted from the calibration using the given weighting approach. As it is written in the plot legend, the CRNS product,* $\theta(N, N_0)$ *was fitted to (i.e., calibrated against) the soil moisture data of the revised weighting approach. We will add a new flow chart as a new Fig. 3 (Fig. 2 in this very document) to better clarify how weighting approaches and calibrations are connected.*

1.17. Figure 6, “CRNS fit to revised”

RC: ***It is not clear how the “baseline” in-situ soil moisture observation was calculated here? (by equally weighting?)***

AR: *We hope that the previous comment answered the question.*

1.18. Section 4.5

RC: ***This is too brief to be a sub-section.***

AR: *Agreed. We will move the content of this section to the conclusions. We will further move descriptive parts of Table 1 to an additional table in section 3. We will further change the current table by including information about the results of the performance gain for each site. We hope that the suggested additional table and the summary table of the results would accomodate the wishes of the reviewers to add more overview elements and structural clarity to the paper.*

1.19. P22 L22

RC: ***This means the standard sampling scheme, using equal weighting for vertical and horizontal?***

AR: *Yes. Even both, the equal and conventional approach led to less performance. We will rephrase the text to clarify this.*